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THE MEASUREMENT
OF
INDUCTION SHOCKS

A MANUAL FOR THE QUANTITATIVE USE OF FARADIC STIMULI

BY

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PREFATORY NOTE

THE method of measuring induction shocks described in the following pages was developed in a series of papers published between 1908 and 1911 in the American Journal of Physiology. Extended use of the method by myself and coworkers has shown it to have great value in many physiological and psychological researches. In order to make the method more readily available for investigators, and with the hope that thereby quantitative studies may be more generally made, the scattered material of the original papers has been assembled into the form herein presented. Since the work aims to serve rather as a manual than as an exposition of principles, only so much theoretical matter is included as is necessary to make intelligible the procedures adopted.

E. G. M.

BOSTON, *April*, 1912.

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INDUCTION SHOCKS

CHAPTER I

THE CHARACTERISTICS OF INDUCED CURRENTS

Introductory. The inductorium has become one of the most familiar and most useful instruments in the physiological laboratory. There are few physiological researches which do not involve artificial stimulation of tissues; and for the production of stimuli induction shocks are in most cases the first choice. They are easier to use and they subject the stimulated tissue to less permanent modification than do other forms of artificial stimulus. Induction shocks are, however, very variable in intensity; and as commonly used there is no means of knowing or of stating their physiological effectiveness in other than the most general terms. An induction shock is weak, medium, or strong. More closely than that the user does not attempt to describe it.

This lack of knowledge as to the strengths of the stimuli employed is often a serious handicap in the prosecution of individual researches, particularly such as call for the use of stimuli of varying strengths. It also operates to make uncertain the attempts of investigators to duplicate the experiments of others.

No one will question the desirability of being able to measure faradic stimuli, both for the sake of controlling the stimuli used in one's own experiments, and also in order that these stimuli may be so described as to enable other workers to duplicate them as occasion arises.

The purpose of this work is to outline a system for calibrating the apparatus used in generating induction shocks, so that the value of the shocks may be expressed in terms of stimulation units; these units to be applicable to any properly constructed induction apparatus, and to be based upon determinations which can be made in any ordinarily equipped physiological laboratory. The system proposed is not a new departure, but is an extension and amplification of previous systems.

Historical. The phenomenon of electromagnetic induction was discovered by Faraday in 1831, and its physical characteristics were very thoroughly worked out by him and by Henry about the same time. The first suggestion for the physiological use of induction shocks appears to have been made by Sturgeon* in 1837, and from that time to the present their use in this connection has continued.

Various forms of induction apparatus have been devised, but for physiological purposes only one has come into common use; this form, designed by E. du Bois-Reymond * in 1848, is illustrated in Figs. 1 and 2. Such modifications of this design as have arisen since its introduction have to do only with details, and not at all with the underlying principle of the apparatus.

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* Annales de Sturgeon: 1837, p. 477.

Structure of the Inductorium. The induction coil, as adapted by du Bois-Reymond to physiological use, consists, in essence, of two coils of carefully insulated copper wire. One of these, the *primary* coil, is made up of two or three layers of rather coarse wire wound upon a hollow core of nonconducting material. Usually the outside diameter of this coil is about 2.5 to 4 cm., and its length between 8 and 14 cm. The number of turns

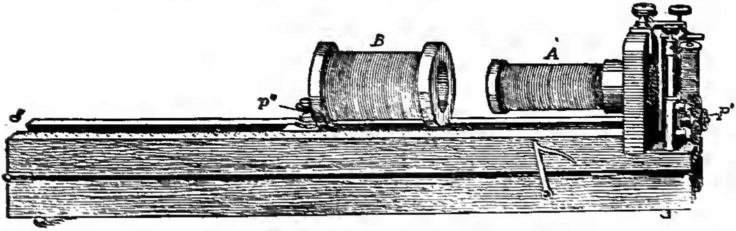

Fig. 1. The induction coil as used for physiological purposes (du Bois-Reymond pattern): *A*, the primary coil; *B*, the secondary coil; *P'*, binding posts to which are attached the wires from the battery — they connect with the ends of coil *A*; *P''*, binding posts connecting with ends of coil *B*, through which the induction current is led off; *S*, the slide, with scale, in which coil *B* is moved to alter its distance from *A*.

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* du Bois-Reymond: Unters. über tierische Electrizität, 1848, Bd. I, S. 447; also, Bd. II, 1, S. 393.

of wire does not ordinarily exceed 600. The coil is mounted horizontally by one end upon a suitable support. The ends of the wire are brought to two binding posts, situated at some convenient place on the support.

The other coil, the secondary, consists of numerous turns of very fine insulated wire, wound upon a hollow spool whose inside diameter is such that the secondary coil can be brought over the primary. The number of turns of wire is usually between 5000 and 10,000. The length of the secondary coil is about equal to that of the primary. The ends of the wire are brought to binding posts mounted upon the spool. A slide, 30 or 40 cm. long, projects from the support of the primary. The secondary is mounted upon this slide with its axis coincident with the axis of the primary. A scale, graduated in millimeters, is mounted on the slide. A pointer on the secondary coil is so placed that it indicates zero on the scale when the secondary covers the primary completely. A device for making and breaking the primary circuit automatically is usually included as part of the apparatus; and a bundle of soft iron wire, so constructed as to slide into the hollow core of the primary coil, is likewise provided.

Principle of the Inductorium. Whenever a steady current is flowing through the primary coil there exists about it a magnetic "*field of force.*" This field may be pictured as consisting of "*lines of force*" each of which passes lengthwise through the primary coil, and, extending a greater or less distance from it into space at either end, curves outward and back so that the two ends meet, making each "line of force" a closed ellipse. The lines of force are very numerous near the primary coil, but become less and less frequent as the distance from the coil increases. The number of lines of force present and the distance from the coil at which they can be detected depend upon the intensity of the current flowing through the coil.

If another coil of wire, the secondary, be placed within the field of force about the primary in such position that lines of force pass lengthwise through it, any *alteration* in the number of lines of force comprehended within the secondary generates within it a current which is the *induced* current. This current, which depends upon *changes* within the field of force, ceases to be generated whenever the field of force becomes steady, and outlasts the change in the field only the brief fraction of a second required for the current to die away. The *direction* of the induced current depends upon the direction of the current through the primary coil, and also upon whether the change in the field is an increase or a decrease in the number of lines of force. The *intensity* of the currents induced in any secondary coil depends upon the number of lines of force moving through it, and also upon the *rate* of their movement; the more rapid the change in the field, the higher the intensity.

The method used in physiology for bringing about alterations of the field within the secondary coil is to make and break the current through the primary.

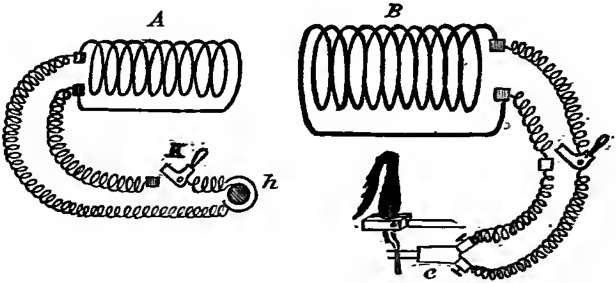

FIG. 2. Schema of induction apparatus (Lombard). *h* represents the galvanic battery connected by wires to the primary coil *A*. On the course of one of these wires is a key, *k*, to make and break the current. *B* shows the principle of the secondary coil and the connection of its two ends with the nerve of a nerve-muscle preparation. When the battery current is closed or made in *A*, a brief current of high intensity is induced in *B*. This is known as the making or closing shock. When the battery current is broken in *A*, a second brief induction current is aroused in *B*. This is known as the breaking or opening shock.

When the primary current is made there is a sudden increase in the lines of force cutting the secondary coil; when the primary current is broken these lines of force suddenly disappear. The currents induced by the make and the break of the primary circuit are obviously of very short duration, since the time required to establish the field of force on the one hand, and for its disappearance on the other, is measured in thousandths of a second, and, as we have seen, only during these periods do induced currents flow. The current induced in the secondary by the *make* of the primary circuit is usually spoken of in physiology as the make shock; that induced by the *break* of the primary is the break shock.

A feature of induction shocks which commends them particularly to the physiologist is the ease with which their intensity may be varied. For securing this variation advantage is taken of the dependence of the induced current upon the number of lines of force which cut the secondary coil. There are two ways of varying this number: One is by changing the intensity of the primary current; the other, by shifting the position of the secondary coil with reference to the primary. This latter method is the one used in the du Bois-Reymond inductorium, and it is a very satisfactory method, since by means of it the strength of the stimulus can be varied several hundredfold, from the maximum for the apparatus to a value negligibly small, by simple shifting of the secondary from one end of its slide to the other. Many inductoria are so constructed that the secondary coil can be rotated about an axis midway of its length. In this way the intensity of the induced current can be cut down to zero, since when the secondary is at right angles to the primary no lines of force pass lengthwise through it. For quantitative purposes, however, it is better to have a rather long slide and to keep the secondary coil always with its axis coincident with that of the primary.

The Form of Make and Break Induced Currents. When a circuit is closed through the primary coil of an inductorium there is a growth of the current within this coil from zero to its full value. Coincidently with this growth of current there is being established a field of force about the coil, and if there is a secondary coil within this field a current is being induced therein. This induced current also begins at zero and increases in intensity during the establishment of the field of force about the primary. As soon as the field is fully established, so that movement of the lines of force ceases, there is no further induction and the current within the secondary dies away. We may represent the successive changes in intensity of the induced current by a curve such as that shown in Fig. 3 in which the height of the curve at any point represents the intensity of the induced current at that instant.

The rise of the make induced current from zero to the maximum, although rapid, is by no means instantaneous, there being a well marked delay in the establishment of the current through the primary coil after the circuit is closed. This delay is due to the phenomenon of *induc-*

tance within the primary coil. This phenomenon may be explained as follows: When the current sweeps through any turn of wire of the primary coil it tends to establish a field of force about that turn; but as the lines of force composing this field cut through adjacent turns of wire of the primary they induce currents therein. Since energy is expended in this inductance the currents thus induced cannot be in the same direction as the inducing current; inasmuch as if they were, there would be a gain of energy — a thing impossible; they oppose the inducing current and allow it to reach its full value only after it has yielded the energy necessary for the inductance. In Fig. 3 the line *AB* represents the time occupied by the primary current in establishing itself against the inductance, and therefore the time during which the induced current increases.

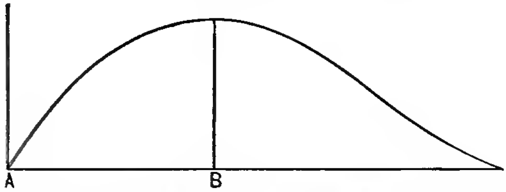

FIG. 3. Curve illustrating the growth and decline of a make induced current. *AB* represents the time required for the primary current to become fully established.

Any condition which diminishes the inductance within the primary coil, thereby allowing the primary current to establish itself more quickly, will not only make the ascending limb of the curve of Fig. 3 steeper, but will also carry it higher; that is, the current induced in the secondary will not only reach its maximum intensity more quickly, but that maximum will be greater; this result being due to the fact that the intensity is greater the more rapid is the alteration in the field of force cutting the coil.

While a current is flowing steadily through the primary coil no induction is manifest; but when the current is broken there is produced in the secondary coil a break induced current. The agency generating this current is the sudden withdrawal of the field of force from the secondary coil.

With the breaking of the primary circuit it would seem at first thought that the lines of force should disappear instantly and that there should be an instantaneous leap of the break induced current from zero to maximum. As a matter of fact the growth of the break current, although very rapid, is not instantaneous, for the reason that with the breaking of the primary circuit the energy absorbed from the current at its make by the inductance within the coil is released and manifests itself as the "extra current," jumping across the points of broken contact as a spark and prolonging slightly the decay of the primary current.

The chief difference between Fig. 10, p. 33, which represents the course of a break induced current, and Fig. 3, representing a make current, lies in the greater steepness of the ascending limb of the curve of the break current, due to the shorter period occupied by the spark in passing. Here again any condition that hastens the passage of the spark brings about increased intensity of induced current by accelerating the disappearance of the field of force.

Since under most conditions the delay in establishing the primary current, due to inductance, is greater than the delay in its disappearance, from sparking at the contacts, make shocks are usually less intense physiologically than are break shocks.

CHAPTER II

FACTORS WHICH AFFECT THE STRENGTHS OF FARADIC STIMULI

ANY scheme for measuring induction shocks, if it is to be wholly satisfactory, must take into account all the sources of possible variation present in the mechanisms by which the shocks are generated and applied to tissues. The numerous methods which have been worked out hitherto have been uniformly based upon sound physical principles, and give accurate results so far as they go; they leave something to be desired, however, in that none of them deals with all the conditions of variation which are actually present whenever tissues are stimulated, and their usefulness is limited by just that much. The justification for the present work lies in its attempt to take into account all the sources of variation which exist. These are to be divided into those whose influence upon the strength of stimuli is in accordance with mathematical laws, determinable by the experimenter, and those which are not apparently so determinable. The former are made the basis for the system of measuring stimuli herein described; the latter are studied with a view to showing how their effects may be minimized.

Sources of Variation. The induction apparatus, as used in the physiological laboratory, consists of two circuits: the primary, or inducing circuit, which includes the primary coil of the inductorium, a source of current, and a device for making and breaking the circuit, together with the necessary connecting wires; and the secondary circuit, including the secondary coil, wires leading thence to suitable stimulating electrodes, and the tissue to be stimulated. In Fig. 2, p. 6, these circuits are illustrated diagrammatically.

In any given primary circuit variations may arise either in the amount of current yielded by whatever source of current is used; or in the key, whereby the circuit is made and broken. In any given secondary circuit variations may arise in the position of the secondary coil with respect to the primary, this being, as we have seen, the usual method of bringing about variations in stimulating strength; in the electrical resistance of the tissue which is being stimulated; and in the contacts between the stimulating electrodes and the tissue to which they are applied. Also different inductoria usually present structural differences, such as different dimensions and different numbers of turns of wire in primary and secondary coils, which themselves bring about wide differences in the strengths of stimuli generated by the different inductoria. The presence or absence of an iron core within the primary coil is also a source of great modification of stimuli. Finally, as we have seen, there is a difference in physiological effect between make shocks and break shocks.

Of the sources of variation just described the following are subject to laws which are determinable, and are to be included, therefore, in our quantitative scheme: The construction of the inductorium, the position of the secondary coil with respect to the primary, the presence or absence of an iron core in the primary, the intensity and voltage of the primary current, the use of make or break shocks, the electrical resistance of the stimulated tissue and the mode of contact of the stimulating electrodes with the tissue.

The variable which is not determinable is the effect on the stimulus of the manner of making or breaking the primary circuit. This must be, so far as possible, made uniform.

Methods Previously Proposed. The first attempt to measure induction shocks is said to have been made by Rosenthal in 1857.* Two years later Pflüger made quantitative comparisons between shocks, varying their intensities by varying the primary current, leaving all other factors constant. His method gives accurate relative results, but seems not to have commended itself to physiologists, probably because it calls for a rather complex mechanism for varying and at the same time measuring the primary current.

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* See Garten: Handbuch der physiol. Methodik, 1908, Bd. II, Abt. 3, S. 393.

The earliest method of measuring induction shocks which received wide recognition was worked out under the direction of Fick by his student, Meyer, in 1869.* This method concerned itself altogether with the effect upon the intensity of break shocks of shifting the position of the secondary coil relative to the primary, and amounts, therefore, to a calibration of the slide upon which the secondary coil moves. By such calibration the relative intensities of the shocks given by the inductorium at the various secondary positions are accurately indicated, *so long as all the other variable factors remain unchanged.* A similar calibration is an essential feature of any scheme for the quantitative use of the inductorium, and indeed the only criticism of the Fick method of measuring stimuli is for its incompleteness. The Fick calibration was accomplished by including in the secondary circuit a galvanometer and determining the current induced in the secondary coil at its various positions by the deflection produced when a given current was made or broken through the primary. This method, although simple in theory, was in fact rather difficult to put into practice with the electrical measuring apparatus available in Fick's time; and accordingly

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* Meyer: Unters. phys. Labor. d. Züricher Hochschule, Wien, 1869, S. 36.

Kronecker,* in 1871, introduced a modification of the method whereby its application was simplified. He used two inductoria, connected their secondary coils in series with a galvanometer and connected both primary coils with a single source of current in such fashion that the two secondaries gave induced currents opposite in direction when the primary circuit was broken. Thus the galvanometer deflection was used merely as an indicator that one induced current was stronger than the other, rather than as a measure of the strength of the induced current itself.

With both secondaries at zero the primary current was broken and the amount and direction of deflection noted. The coil giving a stronger shock was then moved outward till no deflection occurred. Then the weaker coil was moved outward till a deflection equal to the first one was obtained. This procedure was repeated till the whole length of the slide had been traversed, the number of times the stronger secondary was moved being noted. If this number is multiplied by the original galvanometer deflection we have a value which expresses how many times greater the galvanometer deflection would be with the secondary at zero than at the end of the slide. To calibrate the slide on the basis of 1000 units, as Kronecker does, the total deflection noted above is divided by 1000 and the quotient gives the galvanometer deflection per unit. If now the weaker coil is set at zero and the stronger at a point such that the galvanometer deflection is that called for per unit, it is possible, by repeating the original procedure, to divide the scale into 1000 parts, each of which represents a given galvanometer deflection, and therefore an equal decrement in stimulating value. This method has the advantage that after one inductorium is calibrated it is extremely easy to calibrate others to correspond with it, by connecting the calibrated and uncalibrated coils in the manner described above and finding the corresponding points on the two slides. Kronecker, by substituting a telephone for the galvanometer, made the taking of readings even more simple.

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* Kronecker: Arbeiten aus der physiologischen Anstalt zu Leipzig, 1871, S. 186.

The method has the disadvantage that it is purely arbitrary, depending at the outset on a chance difference of stimulating strength occurring in two inductoria; for this reason the calibration can only be duplicated through access to a coil already calibrated. An observer, unable for any reason to obtain a Kronecker coil, might, it is true, prepare a calibration of his own by repeating Kronecker's original procedure, but he could not know whether his units represented the same stimulating values as the corresponding Kronecker units, and so could not express satisfactorily the strengths of stimuli used by him.

v. Fleischl,* in 1875, proposed a method of calibrating the inductorium in which for the galvanometer deflection was substituted the threshold contraction of a nerve-muscle preparation. In this calibration the decreases in stimulating value which result from moving the secondary coil outward were compensated by increasing the current through the primary coil, the increases required being taken as the measure of the change in stimulating intensity resulting from the movement of the secondary. This method has the advantage of being available in situations where no galvanometer can be obtained. Its greatest importance lies, however, in confirming the assumption of Fick and of Kronecker that the physiological intensities of break induced currents are proportional to the galvanometer deflections they produce.

Wertheim-Salomonson† has recently described a method for obtaining a physiological calibration in which variations in the primary current are avoided. He places the nerve of the nerve-muscle preparation to be used as an indicator in one branch of a divided secondary circuit, and in the other branch places a resistance equal to that of the nerve. (See Fig. 4.) The resistance of the divided circuit is then one-half that of the nerve alone. By placing in the circuit beyond the shunt another resistance equal to one-half that of the nerve the total resistance of the secondary circuit is made equal to what it would be if the shunt and the added resistance were both removed. Since, however, the nerve is in a divided circuit, both branches of which have equal resistance, it receives only one-half the current generated in the secondary coil. That secondary position at which the nerve receives threshold stimulation when in the divided circuit is determined, and then the shunt and the additional resistance are cut out. Now the nerve receives the whole current from the secondary instead of half of it, and if the secondary position is found at which the threshold stimulus is again imparted we know that this second current has just half the stimulating value of the first. We have thus a method for comparing stimuli, which admits of extension sufficient for the complete calibration of a coil. It has, however, the shortcoming, already noted for Kronecker's method, of giving values applicable only

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* v. Fleischl: Sitzb. d. k. Akad. d. Wissensch. Wien, 1875, Bd. lxxii, Abth. III. Also Ges. Abh., 1893, S. 475.

† Wertheim-Salomonson: Zeitschr. f. Elektrother. I., 1899, S. 97.

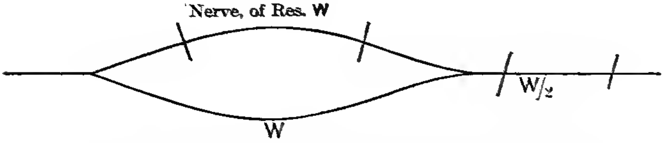

FIG. 4. Diagram showing method of inserting resistances in the Wertheim-Salomonson method of calibration. After Gasten.

to the single coil on which it is worked out. One very important feature of a wholly satisfactory calibration must be its general applicability, so that any properly constructed inductorium can be calibrated in any laboratory to give results comparable with those obtained from other calibrated instruments.

Moreover, it is not to be forgotten that no method of calibration thus far described takes into account the effects of strength of primary current, of tissue resistance, or the method of applying the stimulating electrodes, all of which are important, and at the same time determinable, and therefore to be included in a complete calibration scheme; nor do any of them consider the strength of make shocks, all being available only for breaks.

A device which is superior in certain respects to any thus far described for measuring stimuli is the "faradimeter" of Edelmann. In this apparatus a galvanometer in the secondary circuit registers the voltage of the induced current. The galvanometer readings give correct indications of the values of stimuli only when a current of definite, fixed amperage is broken in the primary circuit. It is necessary, therefore, to have a source of currents specially selected to give this amperage, and by means of an ammeter in the primary circuit to insure that it is maintained. The Edelmann method is an advance over others in that it takes account of the factor of primary current strength and provides for its regulation. It does not, however, take account of the influence upon the strength of stimulus of variations in tissue resistance, since the quantity measured by the galvanometer, namely the voltage, is independent of the resistance. Nor does it consider the effect of the method of application of the stimulating electrodes. But so long as these two factors remain constant the Edelmann faradimeter gives accurate results for break shocks, and expresses them in terms such that the stimuli used by one worker can, save for the factors above mentioned, be duplicated by others.

The importance of taking secondary resistance into account was brought out by Hoorweg* in 1893. He demonstrated the effect of variations in resistance in modifying stimulation strengths, and emphasized the necessity of working out some method by which to ascertain this effect. At his suggestion Giltay † designed an electrodynamometer by which the variations in strength of stimulus due to varying secondary resistances can be read directly. This apparatus fulfils admirably the purpose for which it was designed. It is, however, of little practical use in physiology, since its readings, to be comparable, must be made with the same inductorium or with inductoria of precisely similar construction, and the position of the secondary coil with respect to the primary must not be altered. In view of the fact that moving the secondary coil is the usual method among physiologists for varying the strength of stimulus, this instrument clearly does not altogether meet the requirements of physiological work. It has, moreover, the somewhat serious shortcoming of taking no account of the method of applying the stimulating electrodes, so that, even were all the other conditions met, the electrodynamometer would still fail to give wholly complete measurements.

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* Hoorweg: Die medicinische Elektrotechnik und ihre physikalischen Grundlagen, Leipzig, 1893.

† Giltay: Annalen der Physik und Chemie, 1893, Bd. 50, S. 756.

Our examination of the various systems hitherto proposed for measuring induction shocks bears out the statement made at the outset that none of them meets fully the requirements of quantitative work. We are justified therefore in submitting a system which, although not new, being an extension of the Fick-Kronecker method, attempts to deal with all the factors concerned in the production of faradic stimuli, so that henceforth the values of stimuli may be expressed in such terms that they can be duplicated or modified quantitatively at will.

CHAPTER III

A SUMMARY OF PROCEDURE

For the convenience of users of the method herein presented it has been thought worth while to describe briefly at the outset the various pieces of apparatus used and to summarize the various procedures involved in making the necessary calibrations and in using the calibrated apparatus.

Instruments Required for the Calibration. The inductorium to be calibrated should be of "standard" construction (see p. 88), that is, it should have a secondary coil approximately 13 cm. long and having about 10,000 turns of wire. The number of turns and the mean cross section of the secondary coil must be accurately known (p. 55). The slide upon which the secondary moves should be not less than 30 cm. long. It should be accurately graduated in millimeters, and a pointer fixed to the secondary coil in such position as to stand at zero when the secondary is pushed completely over the primary. To increase the stimulating effectiveness of the instrument the primary coil should have a core made of a bundle of soft iron wires.

In addition to this inductorium there is needed a constant source of current sufficient in amount to yield at least 1 ampere through the resistance of the primary coil. Where a charging current is available, probably a good storage battery will be found most convenient as a source of current. Several Daniell cells in series, however, answer every purpose. A good ammeter for measuring the intensity of the primary current is required, as is also a variable resistance for adjusting its amount. Since it is often necessary in the course of the work to use currents ranging from 0.0001 ampere to 1 ampere the ammeter must be able to cover this range. No instrument is, of course, able to measure the small currents with sufficient accuracy and at the same time to give direct readings for the larger ones. To give the ammeter the desired range, therefore, recourse must be had to a system of shunts. I have found it convenient to use a milammeter having a scale capacity of 10 mil am-

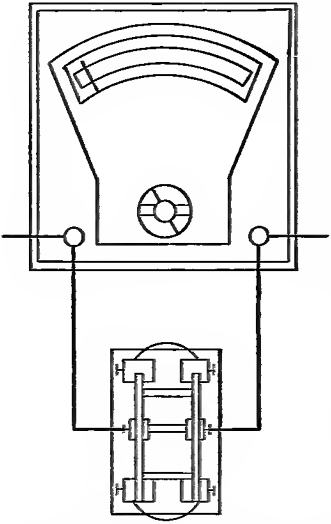

Fig. 5. Diagram showing ammeter shunt made from a Porter metal-contact rocking key.

peres and reading directly to 0.1 mil ampere, and to provide it with two shunts, one adjusted to carry nine-tenths of the total current, the other to carry ninety-nine one-hundredths of the current. For these shunts I use an ordinary Porter metal-contact rocking key connected as shown in the diagram, Fig. 5. For the $\frac{9}{10}$ shunt, German silver wire is used between one pair of end contacts; for the $\frac{99}{100}$ shunt, copper wire is used between the other pair of end contacts. To calibrate the shunts, resistance is introduced into the ammeter circuit until exactly 0.01 ampere is flowing; then the shunts are adjusted until the ammeter reading is exactly 0.001 ampere, when the $\frac{9}{10}$ shunt is in circuit, and 0.0001 ampere when the $\frac{99}{100}$ shunt is in. The shunts must be recalibrated at frequent intervals, but this is not a difficult task.

As a means of adjusting the amount of primary current flowing I have found a dial resistance box most satisfactory, although any available variable resistance can be used. The total resistance should not be less than 11,000 or 12,000 ohms, since with a source of current yielding 2 volts that amount of resistance is often necessary to cut the current down to the point where threshold stimuli are produced.

For making and breaking the primary circuit some form of automatic key is required. A satisfactory one is described in Chapter IX. Experience shows that trustworthy results cannot be obtained with a key which fails to give uniform breaks. Uniform makes are very desirable, but for many sorts of work, including the routine of making the calibration, make shocks need not be employed.

All the apparatus thus far described is required for the quantitative use of the induction coil as well as for its calibration. Additional instruments needed for making the calibration are a good ballistic galvanometer and a standard induction apparatus. A satisfactory form of ballistic galvanometer is the d'Arsonval wall instrument with moving coil and reflected scale, read with a telescope. The standard induction apparatus can be made in any machine shop. It consists of a primary coil, at least 75 cm. long and composed of a single layer of heavy insulated wire, carefully wound, and a secondary coil, not over 15 cm. long, of about 2000 turns of fine wire, placed exactly at the center of the primary coil. The cross section and number of turns per centimeter of the primary coil must be known, and the total number of turns of the secondary.

Additional apparatus required in the use of the inductorium, but not in the calibration, is, first, a device for determining tissue resistance, and, second, suitable stimulating electrodes. I have found the Kohlrausch method of measuring resistance perfectly satisfactory (see p. 72). This method requires an ordinary meter bridge, a small inductorium to give an alternating current, a telephone receiver for an indicator and a resistance box. By suitable wiring, illustrated in Fig. 15, p. 73, a single resistance box can be used both for varying the primary current and as the known resistance in the Kohlrausch determinations.

The stimulating electrodes must be selected with special reference to uniformity of contact. Accurate quantitative results cannot be gotten under conditions of contact variation. For the direct stimulation of muscles I have found platinum needle electrodes most satisfactory. A piece of platinum wire 2.5 to 3 cm. long, and 0.5 mm. in diameter, pointed somewhat at the end with a file, is soldered to a suitable length of very fine copper wire (diameter 0.2 mm.). The platinum needle is thrust directly into or through the muscle tissue; the copper wire, carried to the secondary terminal, affords the very flexible connection necessary for avoiding interference with the free movement of the muscle.

For stimulating nerves the glass-inclosed electrodes described by Sherrington * are as reliable as any I know of. They answer well either for the stimulation of nerves deeply imbedded within the body, or for stimulating the nerve of the ordinary nerve-muscle preparation. In the use of this form of electrode care must be taken that the

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* Sherrington: Jour. of Physiol., 1909, xxxviii, p. 382.

interior of the glass tube is clear of liquid. The electrode is shown in Fig. 6; contact is made by rotating slightly the stopper carrying the two platinum wires.

For the determination of "specific" stimulation values (see p. 76), a rather large known resistance, ten thousand to twenty thousand ohms, must be arranged to be included in the secondary circuit as required.

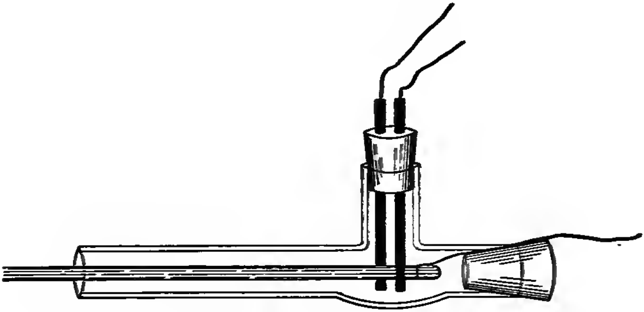

FIG. 6. Shielded electrodes (Sherrington).

The arrangement of apparatus for making the calibration is illustrated diagrammatically in Fig. 7. The procedure is by the following steps, for each of which a page reference is given.

1. Determination of the formula for core magnetization (p. 43).

2. Determination of the mutual induction for a series of selected secondary positions from 12 cm. outward (p. 38).

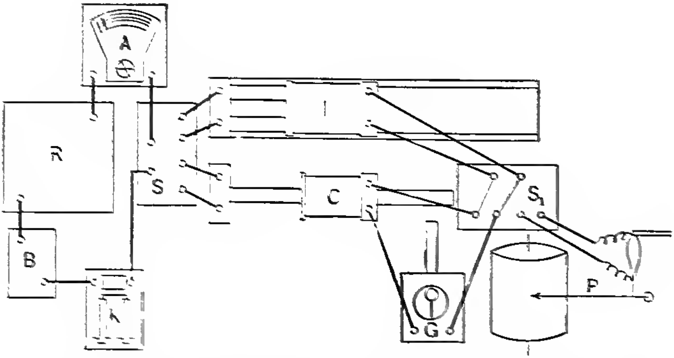

FIG. 7. Arrangement of apparatus for calibrating the inductorium. *A*, ammeter; *B*, battery; *C*, standard coil; *G*, galvanometer; *I*, inductorium to be calibrated; *K*, make and break key; *P*, apparatus for physiological calibration; *R*, resistance box; *S* and *S*₁, switches.

3. Determination of the inductance of the secondary coil (p. 50).

4. Determination of $\frac{M}{L}$ for the secondary positions whose mutual inductions have been established (p. 55).

5. Physiological corroboration of this calibration by the v. Fleischl method (p. 50), accompanied by physiological determination of the "calibration numbers" for the inner secondary positions (p. 58).

6. Construction of a curve to establish calibration numbers for intermediate secondary positions (p. 56).

7. Determination of the constant *C* in the formula for make shocks (pp. 94 and 104).

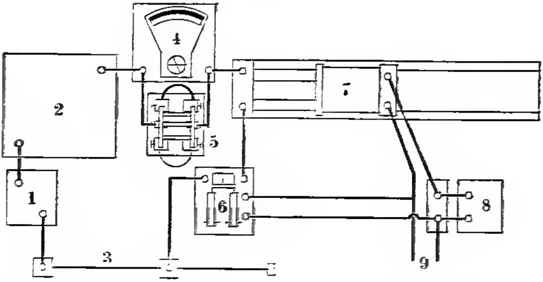

FIG. 8. Arrangement of apparatus for the use of the quantitative method. *1*, battery; *2*, resistance box in primary circuit; *3*, slide wire resistance for fine adjustment; *4*, ammeter; *5*, ammeter shunt; *6*, make and break key with automatic short-circuiting device for make or break shocks; *7*, inductorium; *8*, resistance box in secondary circuit; *9*, wires leading to stimulating electrodes.

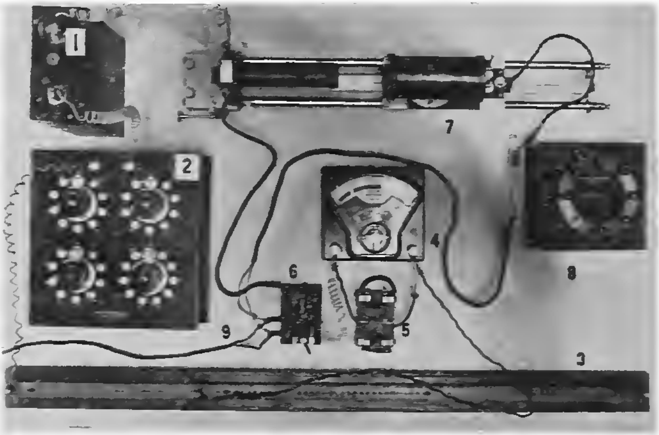

FIG. 9. View of apparatus in actual use. Significance of numbers is the same as in Fig. 8.

The arrangement of apparatus for the use of the quantitative method is indicated diagrammatically in Fig. 8. The diagram is self-explanatory. As an additional guide, a photograph of a set of apparatus in actual use is reproduced in Fig. 9. In the final chapter of the book various precautions are described which much experience with the method has suggested.

CHAPTER IV

THE PHYSICAL PRINCIPLES UNDERLYING THE MEASUREMENT OF BREAK SHOCKS

HELMHOLTZ* appears to have been the first to study in detail break induction shocks. He established the principles which are still accepted as to their formation and course. His work was chiefly from the physical standpoint, although he gave attention also to the physiological aspect of the problem. More recently Fleming † has given a clear and concise discussion of break induction shocks, his presentation agreeing in every essential particular with the earlier one of Helmholtz. The following statement is, in the main, condensed from Fleming's discussion.

The Course of Break Induced Currents. The current induced in a secondary coil by the breaking of the primary current may be represented graphically by such a curve as is given in Fig. 10, beginning at zero, increasing rapidly to a maximum, and then falling more slowly away to zero. If the break of the primary were absolutely instantaneous, the initial rise would be instantaneous likewise and the secondary current would begin with its maximum value. Since, however, there is always, even under most favorable conditions, a certain amount of sparking at the contacts, there is never an instantaneous break, and the initial rise is constantly present. Helmholtz * demonstrated, with the aid of an ingenious apparatus, that the physiological effect of a break induced current is chiefly exerted by that part embraced within the ascending limb of the curve. By breaking the secondary current at various points in its course he found that the physiological effect was virtually as great when the current was broken at the moment of reaching its maximum intensity as when it was allowed to run its entire course. Recent investigations carried out by means of short galvanic currents have shown, it is true, that the stimulating effectiveness of a shock is to some extent dependent as well upon the descending portion of the curve,† so that

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* Helmholtz: Poggendorf's Annalen der Physik und Chemie, 1851, lxxxiii, S. 536. Also, Ges. Abh., S. 459.

† Fleming: The Alternate Current Transformer, London, 1892, i, pp. 184 *et seq.*

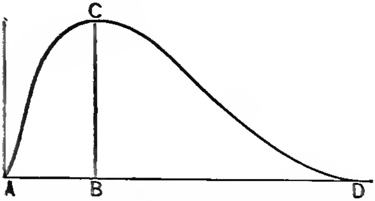

Fig. 10. Curve illustrating the course of a break induced current — after Fleming.

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* Helmholtz: Loc. cit., S. 537.

† Gildemeister: Pflüger's Archiv für die gesammte Physiologie, cxxxi, 1910, S. 199.

Helmholtz' conclusion is not wholly valid. But at this stage of the discussion we may neglect the effect of the descending portion of the curve, and proceed as though the ascending limb were the sole determining factor.

Since the chief physiological effect is exerted during the growth of the current this effect will be greater the higher the curve rises; in other words, the strength of stimulus tends to be proportional to the maximum intensity of the induced current. In the diagram, Fig. 10, the maximum intensity is represented by the ordinate *CB*, drawn from the base line to the summit of the curve, and with the factors determining the value of this ordinate we are at present concerned.

Helmholtz showed that the induced current reaches its maximum intensity at the instant the spark ceases to pass. The abscissa *AB*, therefore, represents the time occupied by the spark. In a properly constructed apparatus *AB* will be constant. Helmholtz showed also that the value of the ordinate *CB* is approximately equal to $\frac{MI}{L}$, in which M is the mutual induction between primary and secondary, I the intensity of the current through the primary, and L the inductance of the secondary. If the break were instantaneous, making *AB* zero, *CB* would equal the expression given above; it falls below that value more and more as *AB* increases, but so long as *AB* is constant the relation between the true value of CB and the value $\frac{MI}{L}$, which it approximates, does not vary.

We may use the expression $\frac{MI}{L}$, therefore, as a physical basis for the measurement of break shocks, although we must note that the expression will not serve fully, since the factor of secondary resistance is not included in it, nor is there any factor for the influence of the manner of applying the stimulating electrodes. Moreover, the expression is proportional to the strength of the stimulus only so long as the circuit is broken uniformly. The expression serves in our quantitative scheme, therefore, only as a starting point. Its use even so far is justifiable only if physiological tests confirm the applicability of the physical relationships. That they do so completely will be shown in due course.

Our next step is a consideration of the individual factors in the expression $\frac{MI}{L}$ and a discussion of the means whereby they are to be determined.

Of the three factors which make up the expression, one, I, the intensity of the primary current, is an easily measured electrical quantity, and is best determined directly by means of an ammeter in the primary circuit. The other two, M and L, are functions of the construction of the inductorium, either by itself or as modified by the relative positions of the primary and secondary coils. M, the mutual induction between the primary and secondary coils, varies with changes in the position of the secondary relative to the primary, but is fixed for each position. It can therefore be determined once for each position of the secondary coil, and the values thus obtained used in all future calculations.

Since mutual induction is the factor which varies with shifts in the position of the secondary coil relative to the primary, most of the calibrations hitherto proposed amount in effect to determinations of the relative mutual inductions for the various secondary positions. That the stimulating power should theoretically be proportional to the mutual induction so long as the other factors remain constant is obvious from inspection of the expression $\frac{MI}{L}$. That the proportion really does exist is proved by the experimental verification of the Fick, Kronecker, and Edelmann calibrations, as well as by the experiments carried out in the development of the present method.*

L, the inductance of the secondary coil, is a function of the construction of the coil and is therefore constant for any given inductorium except as it is modified by extraneous influences. When the inductorium is used with an iron core in the primary, this acts to modify the value of L whenever the secondary coil is directly over the iron core.

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* Martin: Amer. Jour. of Physiol., 1908, xxii, p. 123.

The methods by which M and L are determined in practice are outlined in succeeding chapters.

CHAPTER V

THE DETERMINATIONS OF MUTUAL INDUCTION BETWEEN PRIMARY AND SECONDARY COILS

In determining the mutual induction for the various secondary positions advantage is taken of the fact that this factor appears in the expression for the integral effect of the induced current. This integral effect is represented in the diagram (Fig. 10), by the entire area $ABCD$; its expression is $\frac{MI}{R}$, in which M and I have the same meanings as hitherto, and R equals the resistance in the secondary circuit. The integral effect can be measured by means of the ballistic galvanometer. For this purpose the secondary of the induction coil under examination is connected in series with a good ballistic galvanometer and with the secondary of a standard induction coil, the latter apparatus being so constructed that the mutual induction between its primary and secondary coils can be computed from the construction of the apparatus and the current through the primary. The special features of its construction are found in the primary, which is a solenoid of one-layer thickness, very evenly wound, and several times longer than the secondary. The lines of force through the secondary, placed at the middle of the primary, are then practically straight. The arrangement of the apparatus is shown diagrammatically in Fig. 7.

The secondary of the inductorium whose values of M are desired is set successively at points 1 or 2 cm. apart. At each point the galvanometer deflection caused by breaking a primary current of known intensity is determined. Since each galvanometer deflection represents a certain integral effect, no matter how produced, and since the integral effect affords means of computing M, a determination of the intensity of current which has to be broken in the primary of the standard coil to produce these same deflections provides all the data required for calculating the values sought. The formula used for computing M is developed in the following manner: The expression for the integral effect is, as stated above, $\frac{MI}{R}$. Let this represent the galvanometer deflection caused by breaking a current of intensity I in the primary of the coil whose values of M are desired. Let the expression $\frac{M'S}{R}$ represent the same galvanometer deflection caused by breaking a current of intensity S through the primary of the standard coil. Equating these, we have $\frac{MI}{R} = \frac{M'S}{R}$. The method of connecting the secondaries is, as stated previously, purposely such that the value of R is constant throughout. It therefore disappears from the equation and we have $MI = M'S$. The value of M' is computed from the construction of the standard coil according to the formula $M' = 4\pi nNAS$, in which n equals the number of turns in the primary coil per centimeter of length, N the total number of turns in the secondary coil, A the area of the cross section of the primary, and S the current through the primary in electromagnetic units. Since this current is measured in amperes, it is necessary in practice to call S the intensity of the primary current in amperes and divide the expression by 10 to reduce to electromagnetic units. The formula for M' then becomes $\frac{4\pi nNAS}{10}$. The value $\frac{4\pi nNA}{10}$ is constant for any given standard coil, and once determined is substituted for M' in the equation $MI = M'S$.

To illustrate the process of determining mutual inductions by this method, suppose the standard coil has the following dimensions:

Number of turns in primary per centimeter...	5.4
Total number of turns in secondary..........	1865
Area of cross section of primary.............	6 sq. cm.

The value of $\frac{4\pi nNA}{10}$ is 75.870, and the equation for mutual induction is $M = \frac{75.870\,S}{I}$. Now suppose that with the secondary coil at 12 cm. from the zero position the breaking of a primary current of 0.1 ampere gives a deflection on the galvanometer scale of 5, and that to secure the same deflection with the standard coil a current of 6.8 amperes must be broken through its primary. Substituting these values in the equation we obtain for M 5,150,000. By repeating this procedure the values of M for every secondary position can be obtained.

If $\frac{MI}{L}$ is a true expression for the physiological effect of break shocks, evidently with L constant the product MI must also be constant so long as it represents a uniform stimulus, no matter how the value of M may be varied by shifting the secondary coil. Experiment shows that MI does remain constant for a constant stimulus over the entire field of the inductorium, except that, when an iron core is present, it varies in the part of the field directly over the iron core. This is the region in which, as stated in a former paragraph, the value of L is affected by the presence of such a core.*

If a constant stimulus gives a constant value of MI, however the secondary coil may be shifted, it follows that if I is made constant,—in other words, if a fixed current is broken through the primary coil,—the strengths of stimulus at different secondary positions must vary directly as the values of *M* for those positions. By determining these values, then, we provide ourselves with a calibration which reveals accurately the effect on stimulating strength of shifting the secondary coil. Such a calibration, as previously stated, is a necessary basis in any scheme for the quantitative use of induction shocks.

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* For experimental evidence, see Martin: Amer. Jour. of Physiol., 1908, xxii, p. 124.

CHAPTER VI

EFFECTS PRODUCED BY AN IRON CORE IN THE PRIMARY COIL

Inasmuch as the almost universal practice in physiological work is to use inductoria with iron cores, a brief discussion of the effects of such cores on stimulation strengths seems desirable at this point. Thus the method becomes at once applicable to inductoria with iron cores as well as to those not provided with them.

The principal effect of the iron core is that which has led to its use, namely a great increase in the number of lines of force surrounding the primary coil, with a corresponding increase in the intensity of the stimuli generated.

Another effect is that noted in a previous paragraph (p. 36), of altering the effectiveness of the stimuli generated when the secondary coil is directly over the primary, so that in these positions MI is not constant for a constant stimulus. The method of correcting the calibration for this effect of the iron core is given in Chap. VIII, p. 58.

The iron core has also an effect upon stimulation strength due to its *magnetisation* by the primary current, an effect which appears, however, only when primary currents of considerable intensity are used. Allowance for this effect in computing the values of MI must be made, whenever I is large, by introducing a correction factor. This factor can be obtained without difficulty by the use of the ballistic galvanometer, since the deflections of that instrument are affected by core magnetization. Inspection of the formula $MI=M'S$ (p. 40) shows that so long as M and M' remain constant, I, the current through the primary of the coil under examination, must vary directly as S, the current through the primary of the standard coil. This relationship is found by experiment to hold in ordinary induction coils for values of I up to 0.1 ampere, but above that point the value of S is always larger than the equation calls for. In other words, when core magnetization is present the primary current produces a greater deflection than it does in the absence of this effect. The variation due to the magnetization of the core is not very difficult to correct, because, as repeated experiment has shown, the ratio between the actual values of I and those computed from the values of S depend upon an easily determined factor which is constant for any given iron core.

To determine this factor some position of the secondary coil must be selected at which primary currents up to 1 ampere give galvanometer deflections not greater than the entire scale. With the secondary in this position primary currents of increasing intensity, beginning at about 0.01 ampere, are broken, and the deflections produced by each carefully noted. Then with the standard inductorium the values of S giving these same deflections are determined. Although at first the ratio of S to I remains constant, as the values of I begin to exceed 0.1 ampere the ratio steadily increases. It is evident, therefore, that large currents are producing relatively greater deflections than small ones. By multiplying the different values of S by the ratio of S to I, which was constant, we obtain a series of computed values of I representing the currents which would be required to produce the observed galvanometer deflections if no iron core were present. These are, of course, the values of I which are to be employed in computing the strengths of stimuli according to the expression $\frac{MI}{L}$.

Table I, column 3, gives the values of I computed from a series of observed values of I and S in actual experiments.

TABLE I

Value of I observed in amperes.	Value of S observed.	Value of I computed in amperes.	Ratio computed value of I to its observed value.	Decimal part of ratio divided by observed value of I.
0.01	0.005	0.01	1.0	....
0.05	0.025	0.05	1.0	....
0.10	0.05	0.10	1.0	....
0.20	0.1044	0.2088	1.044	.22
0.30	0.1597	0.3194	1.065	.217
0.40	0.2180	0.4360	1.090	.225
0.50	0.2782	0.5564	1.113	.226
0.60	0.3396	0.6702	1.132	.22

To derive the equation for obtaining *I computed* when *I observed* is known we determine in a series of experiments the ratios of *I computed* to *I observed* (see column 4 of the table). If now the decimal part of each ratio is divided by its corresponding value of *I observed*, a constant is obtained which represents the number by which *I observed* must be multiplied to obtain this decimal part of the ratio. This constant is shown in column 5. After the constant is found it is used for computing I according to the formula $I_c = I_0 \times (1 + KI_0)$. In this formula I_c is the computed value of I, I_0 is its observed value, and K is the constant, — in the case cited in the table equaling .22.

The method of correcting for the magnetization of the iron core is given in detail since, in spite of the abundant theoretical justification for the omission of the iron core, especially where quantitative estimations are sought, for the practical purposes of the physiologist the inductorium as commonly used, with the iron core present, is usually to be preferred. The intensity of stimulus, other factors being equal, is at least five times greater with the iron core than without it in inductoria of the usual type. This increased efficiency makes it possible to obtain with primary currents of moderate intensity as strong stimuli as the physiologist ordinarily requires. The use of *moderate* primary currents is of great importance in quantitative estimations of induction shocks, since thereby is avoided that heavy sparking at the contacts which always accompanies the break of a current of high intensity, and which affects the intensity of the stimulus in a manner that cannot be foretold.

When the secondary coil of an inductorium is moved from the zero position until nearly clear of the primary coil, it enters a "critical region" where small changes in position are accompanied by great changes in the intensity of the stimuli given by the instrument. The impression seems to prevail among physiologists that inductoria having iron cores show so much greater variations of intensity in this "critical region" than do those without iron cores as to make the omission of the iron core a distinct advantage in many experiments. As a matter of fact, however, Kronecker inductoria, such as are used in most physiological laboratories, show for given changes in secondary position in the "critical region" greater variations in stimulation intensity with cores removed than with cores present. This is apparent when the Kronecker graduations of such coils are compared with the calibrations made for them by the method of the present work (see p. 55). In the preparation of the Kronecker graduations the iron cores were withdrawn from the instruments. For the calibrations made in connection with this work the iron cores were in place.

TABLE II

Effect of the Iron Core on the Rate of Change of Stimulation Intensity in the "Critical Region" of the Inductorium

Position of secondary in centimeters.	Iron core absent.		Iron core present.	
	Kronecker graduation.	Percentage decrease per centimeter.	Author's calibration.	Percentage decrease per centimeter.
8	6190	....	6240	....
9	5150	17.0	5340	14.4
10	4150	19.4	4500	15.7
11	3250	21.7	3600	20
12	2375	27.0	2640	26.7
13	1570	33.9	1920	27.3
14	1000	36.3	1270	33.8
15	625	37.5	860	32.1
16	435	30.4	600	30.3
17	310	28.7	455	24.2
18	230	25.7	350	23.1
19	178	22.7	280	20.0

Table II gives a comparison of the calibrations in the "critical region" of one inductorium made without and with the iron core. The primary coil of this instrument was 14 cm. long. The table shows clearly that the rate of decrease of stimulation intensity from point to point is greater when the iron core is absent than when it is present. Table III is the record of experimental verification of the same fact. Stimulation intensities were compared in these experiments according to the v. Fleischl method (p. 56), namely by comparing the primary currents required to produce stimuli of equal value with the secondary coil at different positions.

According to this method increases in the primary current represent corresponding decreases in the stimulating efficiency of the inductorium.

TABLE III

Experimental Proof that Stimulation Intensity shows Greater Variation in the "Critical Region" when the Iron Core is Absent than when it is Present. Break Shocks

Date of experiment.	Position of secondary in centimeters.	Iron core absent.		Iron core present.	
		Primary current, amperes.	Percentage increase in current.	Primary current, amperes.	Percentage increase in current.
Dec. 21, 1906........	8.0	0.0195	...	0.00187	...
	12.0	0.0505	159	0.00463	148
	16.0	0.260	415	0.022	375
Dec. 24, 1906........	8.0	0.00576	...	0.0008	...
	12.0	0.01523	164	0.00197	146
	16.0	0.091	432	0.00934	374
Apr. 15, 1907.........	8.2	0.017	...	0.0036	...
	11.28	0.035	107	0.0063	75
	12.45	0.0535	50	0.0092	40
	14.0	0.107	100	0.016	74
	16.2	0.2485	132	0.034	112

CHAPTER VII

COMPARISON OF ONE COIL WITH ANOTHER — THE VALUE OF *L*

WE have seen (p. 41) that in any given inductorium, after allowing for certain exceptions due to the iron core, if one is present, the strengths of stimuli produced by a given primary current with the secondary coil at various positions are directly proportional to the mutual inductions for those positions. When, however, the attempt is made to compare the stimuli generated by one inductorium with those produced by another, it is at once apparent that the relation between stimulating value and mutual induction holds only for stimuli produced by the same instrument. This, indeed, was recognized by Helmholtz, who pointed out the necessity of including in the expression for stimulating value the factor L, whereby to take account of the influence of inductorium construction. This factor, according to Helmholtz, is dependent on the inductance of the secondary coil, and is to be derived, therefore, from the expression for inductance. The common formula for the inductance of a coil is $L = \frac{AW^2}{l}$, in which L is the inductance of the coil, A its mean cross section, W the number of turns of wire composing it, and l its length.

When, in the course of developing this method of measuring stimuli, the attempt was made to apply the above expression for L in the formula $\frac{MI}{L}$, the curious observation resulted that it applied perfectly with some inductoria and not with others. That is to say, when equal stimuli were generated by means of different inductoria, equal values of $\frac{MI}{L}$ were given by some, but not by all, of the instruments compared. Upon analyzing the reason for the difference the following fact came out clearly; *equal values of* $\frac{MI}{L}$ *were given by those inductoria whose secondary coils had the same number of turns of wire per centimeter of length, regardless of the total number of turns of wire; unequal values were given by those inductoria whose secondaries had different numbers of turns per centimeter of length.* If we look now at the expression for L given above, i.e., $L = \frac{AW^2}{l}$, and separate within it the factor of turns per unit of length, the expression reads $L = AW \times \frac{W}{l}$. The experimental results showed as stated above that in all the inductoria having the same value of $\frac{W}{l}$, namely the same number of turns per centimeter, the expression $L = AW$ might be substituted for the expression $L = \frac{AW^2}{l}$ and equal values of $\frac{MI}{L}$ for equal stimuli would be given. The next step was to see whether those inductoria which formerly gave non-concordant results would give concordant ones if for the value of L the expression AW, namely the product of the cross section of the secondary by the number of turns in it, were used. It was found that when this was done all the inductoria examined gave for equal stimuli corresponding values of $\frac{MI}{L}$, regardless of the dimensions of the coils, but subject to a certain restriction as to secondary resistance to be discussed later (p. 78). In order to bring this point out clearly some of the experiments upon which it is based are cited below (Table V). The inductoria used are described in Table IV. In this table only those inductoria are considered whose secondaries have different numbers of turns per centimeter, since only by them can be determined which of the two expressions for L is correct. In all the experiments, comparisons were made between the various inductoria and a single one known as coil B. This is a large inductorium with a Kronecker calibration whose secondary has 800 turns per centimeter; it was selected as a basis of comparison merely for convenience.

In Table IV, columns 5 and 6, are given, for the different inductoria examined, the values of $L = AW$ and $L = \frac{AW^2}{l}$. To simplify the comparisons between the various coils the values of $\frac{AW^2}{l}$ as given in Table IV were all divided by 800, the number of turns per centimeter in the secondary of coil B, thus making the value of L for coil B the same by either formula. These values are set down in column 7 of the table. To bring the final results into convenient denominations these figures and also those in column 5 were divided by 100. It is understood, of course, that these divisions, made purely for convenience, in no wise modify the relations between the coils.

In Table V are set down the experimental results of the comparisons between the various inductoria. Since details would only confuse, they are omitted. The figures presented in the table show clearly that the proper expression for L is AW rather than $\frac{AW^2}{l}$.

TABLE IV

Description of inductoria used in establishing expression for *L*

Coil.	Length of secondary coil.	Turns in secondary coil.	Cross section of secondary coil.	Cross section × turns in secondary coil.	$\frac{\text{Cross section} \times \text{turns in sec.}^2}{\text{length}}$	Column 6 divided by 800.
	cm.		sq. cm.			
B	13	10,350	17.6	182,000	145,000,000	182,000
C	7.4	4,830	22	105,000	69,500,000	87,000
F	13.5	3,000	15.4	46,000	10,250,000	12,800
H	9.3	6,000	16.6	100,000	64,300,000	80,000
N	9.3	8,000	17.8	142,000	122,500,000	153,000

TABLE V

Demonstrating that the expression for *L* should be *AW* rather than $\frac{AW^2}{l}$

$\frac{MI}{L}$ coil *B*.	Coil.	$\frac{MI}{AW}$.	$\frac{MI}{\frac{AW^2}{l \times 800}}$.	$\frac{MI}{L}$ coil *B*.	Coil.	$\frac{MI}{AW}$.	$\frac{MI}{\frac{AW^2}{l \times 800}}$.
8	*C*	7.7	4.5	7.5	*H*	7.5	9.4
12.6		13	7.6	7		7.2	9
11.4		11.7	6.9	5.3		5.3	6.6
28.2	*F*	28	100	2.57	*N*	2.43	2.25
17		16.4	57	30.5		28.6	26.5
2.6	*H*	2.8	3.5	64		60	56
30.5		30.9	38.6	10.2		10.4	9.7
64		61.1	76.4	7.5		7	6.5

CHAPTER VIII

THE PREPARATION OF A CALIBRATION SCALE FOR BREAK SHOCKS

IN previous chapters the methods of obtaining the individual factors making up the expression for break stimulation strength have been discussed in detail. To show how these methods are put into practice in preparing an inductorium for quantitative use is next in order. The first step is the determination of the mutual inductions by the method hitherto described, for a series of positions, preferably not more than 2 cm. apart, along the scale. If the instrument to be calibrated is without the iron core these measurements should be taken from the zero position outward; if an iron core is present there is no advantage gained by determinations of mutual induction for secondary positions in the region where the secondary coil overlaps the primary. Having determined these values, each is divided by *L*, the product of the cross section by the number of turns of the secondary coil. The mean cross section must be determined with great care, a rather difficult procedure in completed inductoria, and one which ought to be carried out in connection with their manufacture.

In order that the final stimulation units may be of convenient size the value of L which has been adopted in this scheme is not the direct product of the cross section by the number of turns of the secondary, but is that product divided by 100. Having determined this value, the mutual inductions previously established are divided by it. The resulting figures are the "calibration numbers" for the particular secondary positions to which they apply. To determine the numbers for intermediate positions those determined as above are plotted on a rather large scale on coördinate paper and a smooth curve is drawn connecting them. Since the mutual induction necessarily diminishes, not by fits and starts, but smoothly, as the secondary is moved outward, such a curve, if carefully made, will indicate the calibration numbers for intermediate positions with a high degree of accuracy.

To prove the accuracy of the calibration the method of v. Fleischl is employed (p. 18) in which the minimal contraction of a frog's gastrocnemius is used as the index of a constant stimulus. In detail this procedure as carried out by myself was as follows: The freshly isolated gastrocnemius was suspended by its attached femur in a moist chamber, and its lower end connected by a small copper wire to a muscle lever whose effective weight was about 10 gm.; the muscle was not afterloaded. The lever had a magnification of about ten, and its point pressed lightly upon a smoked drum. The minimal contraction could be detected without difficulty, since the whole apparatus was made rigid enough for the slightest movement of the muscle to show itself at the end of the lever. Connection between the muscle and the terminals of the secondary coil was by means of two platinum needles soldered to fine copper wires leading from the secondary terminals. These needles were thrust directly through the muscle tissue, — one about 5 mm. below its origin, the other the same distance above the distal tendon, both in the same vertical plane. By this method of connecting the muscle, variations in the secondary resistance aside from those in the tissue itself were avoided. At least half an hour was allowed to elapse after the muscle was hung in position before stimulation was begun; in order that summation might not enter, the shortest interval allowed between successive stimuli was ten seconds; to avoid fatigue the strength of stimulus used was always kept as near minimal as possible. The results of repeated experiments show that under these conditions a high degree of constancy is usually maintained during the interval, about three hours, required for a single experiment. That each experiment be complete in itself is, of course, necessary, since no means has suggested itself for obtaining a response which shall remain constant through a period of successive days. To have conditions uniform the electrode nearer to the origin of the muscle was in most cases made the cathode. With the minimal contraction of the muscle as the index, the primary current necessary to arouse it, measured in amperes, is determined with the secondary coil in various positions. To allow for variations in irritability of the tissue the experiment should be repeated a number of times. If the calibration is carefully made in the beginning it will be found that in each individual experiment the product $\frac{M}{L} \times I$, — primary current times calibration number, — is virtually constant, showing that the calibration is correct.

Should the inductorium being calibrated have an iron core, there still remains the establishment of calibration numbers for the region where the secondary coil overlaps the primary. These, however, can easily be determined by extending the experiments, just described for proving the calibration, to cover this part of the field. The value of $\frac{M}{L} \times I$ is established in any given experiment from the part of the field where $\frac{M}{L}$ is known, that is, where the calibration has already been worked out. Since this is constant so long as the stimulus is unchanged a determination of the primary current, I, for this stimulus, in the region where $\frac{M}{L}$ is unknown, yields at once data for computing $\frac{M}{L}$. By averaging several experiments this part of the field can be calibrated with sufficient accuracy.

It must be stated, however, that in the innermost part of the field, including about half of the length of the primary coil from zero outward, the calibration numbers determined by the v. Fleischl method will be found to differ somewhat according as the tissue used as an indicator has high or low resistance, high resistances showing larger calibration numbers than low ones. For this reason it is desirable to avoid using this region in work which requires a high degree of accuracy, unless a calibration has been previously worked out for the resistance actually to be employed. Experience shows that occasions when it is necessary to use the first 5 or 6 centimeters of the scale are of rare occurrence in most kinds of experimental work.

CHAPTER IX

THE MAKE AND BREAK OF THE PRIMARY CIRCUIT

From the beginning of the use of induction shocks for stimulating living tissues investigators have recognized that the physiological intensities of these shocks are markedly affected by the manner of making or breaking the primary circuit. Helmholtz* called attention to this fact in his study of induced currents, and in the discussion of the variable factors to be considered in the attempt to measure induction shocks (p. 14), I pointed out that the manipulation of the primary key is a variable whose influence cannot be mathematically determined, and which, therefore, must be made as uniform as possible.

Before entering upon a discussion of means whereby the manipulation of the primary make and break key can be made uniform, it is desirable to point out briefly the manner in which variations in the break and make of the primary circuit modify stimulating intensities.

In the account of the theoretical basis for the break shock formula, $Z = \frac{M}{L} I$ (p. 34), the statement was made that this expression applies exactly only when the break is instantaneous, although it holds relatively so long as the time occupied by the break does not vary. Since this in turn depends on the duration of the spark, our present inquiry resolves itself, so far as break shocks are concerned, into a study of the conditions governing contact sparking.

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* Helmholtz: Poggendorf's Annalen der Physik und Chemie, 1851, lxxxiii, p. 538.

The duration of the spark at a broken primary contact depends in part upon the intensity of the primary current, in part upon the amount of volatilization occurring at the contact, and in part upon the speed with which the points are separated. This last factor explains why keys operated by hand cannot be depended upon to give uniform results, and why some form of automatic key is required, since only thus can a uniform speed of separation be secured. Moreover, ordinary mercury keys cannot be depended on even when operated automatically, because of the tendency of mercury when not absolutely clean to cling in drops and thus vary the speed with which the contact points actually separate. In practically all keys there is some volatilization; platinum contacts giving the least, ordinary mercury contacts the most. It is impracticable to use always primary currents of a single intensity; but, in primary currents not exceeding 1 ampere, the variation is too slight to be of practical importance.

The *making* of a primary circuit is not attended with sparking, so that the sources of error for makes are not the same as for breaks. As a circuit is made the resistance falls from infinity to the resistance of the closed circuit itself. It is during the change from the first of these resistances to the second that the secondary current is induced. The more nearly instantaneous the change, the greater is the physiological intensity of the induced current. In hand-operated metal-contact keys there can be no assurance that the contact points will be pressed together with the same firmness twice in succession, so that to secure uniformity of contact automatic keys are required for make shocks as well as for breaks. A further and more serious defect in metal-contact keys for make shocks is their liability to rebound slightly, or to slip sidewise, thus giving not a single clean-cut make, but a succession of make, break, and make. So constantly has this defect shown itself in my experiments, even with carefully constructed automatic metal-contact keys, that I have found it necessary to use mercury contacts altogether in studying make shocks.

The considerations stated above lead to the following conclusions: That hand-operated keys are not to be depended on for uniform makes and breaks; that for break shocks platinum contacts are to be preferred to mercury because of their less volatilization, while for make shocks, on account of the rebound or side-slip of metal contacts, mercury affords the only trustworthy contact.

It is, of course, wholly undesirable to equip the primary circuit with two keys, — one of mercury to be used for making the circuit, and another of platinum for breaking it. I shall describe, therefore, an automatic make and break key with mercury contacts which has been proved by several years' experience to give uniform breaks and makes.*

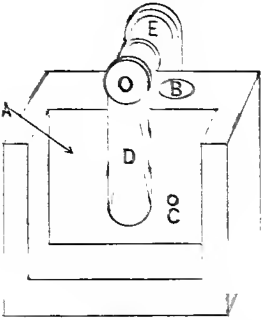

Fig. 11. Diagram illustrating the principle of the vulcanite knife-blade key. The front of the block is broken away to show the relations of the parts within the chamber, *a*. *a* and *b*, mercury chambers; *c*, opening between *a* and *b*; *d*, vulcanite knife blade supported upon axis, *o*, which rotates within collar, *e*.

The key consists of a block of vulcanite 30 mm. long, 20 mm. wide, and 25 mm. deep, having cut in it two vertical chambers (see Fig. 11), one (*a*) rectangular, 20 mm. long, 8 mm. wide, and 20 mm. deep; the other (*b*) cylindrical, 6 mm. in diameter and 20 mm. deep. A hole, *c* (Fig. 11), 3 mm. in diameter, is bored through from one of these cavities to the other at a depth of about 16 mm. Each of the chambers is in electrical communication with a binding post, and when filled with mercury they are in electrical communication with each other through the connecting hole, *c*.

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* Martin: Am. Jour. of Physiol., 1910, xxvi, p. 181.

A strip of vulcanite, *d* (Fig. 11), 18 mm. long, 8 mm. wide, and 1 mm. thick, flat on one side and on the other tapered toward the edges, is supported at the top of the block by a horizontal rod working freely in a collar, *e* (Fig. 11), in such fashion as to press closely against the inner surface of the cavity, *a*, and when rotated about its axis of support to cover or uncover the opening, *c*. When the vulcanite strip is brought over the opening, it cuts the mercury connection between cavities *a* and *b*, and therefore breaks any electric circuit which may include them. This method of breaking a circuit has many points in its favor. The break cannot be delayed through the tendency of mercury drops to cling together, for the severance of the mercury column is not the withdrawal of one mass of mercury from another, but is the forcible interposition of a nonconductor in the path.* Moreover, the vulcanite strip cuts off not only the liquid mercury, but if it fits tightly, as it should, cuts off as well any mercury vapor that may be formed. Thus the effect of volatilization of mercury is minimized. Since the point where the break occurs is beneath a considerable depth of mercury, air does not have access to it, and oxidation does not occur. I have found, as a matter of fact, that the same mercury may be used in one of these keys for months without any appreciable variation in the effectiveness of the break.

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* A device employing the same principle was described by Lombard in 1902: Am. Jour. of Physiol., 1902, viii, p. xx.

When the vulcanite strip is so rotated as to uncover the hole, *c*, the mercury in the two cavities reunites and thus makes the circuit. The reunion of the separated mercury masses should take place as smoothly as possible. To bring this about, the vulcanite knife blade is tapered at the edges so that it may plough through the mercury with as little disturbance as possible.

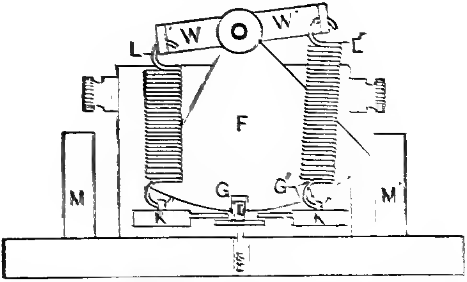

FIG. 12. Diagram of the operating device for the knife-blade key: vertical view. f, triangle of brass bearing slits, g, g', and wings, w, w', rotating about axis, o; l, l', actuating springs; k, k', levers for bringing tension upon springs, and at the same time operating release, i; m, m', stops for limiting motion of knife blade.

The Operating Device. To secure uniformity of action the vulcanite blade must be operated automatically, hand operation being liable to wide variations in the speed with which the contact is made or broken. The method adopted in this instrument is illustrated by the diagrams (Figs. 12 and 13). The axis of rotation of the blade, *o* (Figs. 11 and 12), after passing through the supporting collar, *e* (Fig. 11), is fastened into a triangular sheet of brass, *f* (Fig. 12), from whose apex project horizontally two brass arms, *w* and *w′*; these are bent at right angles at their outer ends, as shown in Fig. 13. From the tip of each of these arms a coiled spring, *l* and *l′* (Fig. 12), extends down to the end of a lever, *k* and *k′*. Each spring consists of twenty-seven turns of spring brass wire, 0.6 mm. in diameter. The length of the spring is about 16 mm., and the outside diameter of the coil 5 to 6 mm. The depression of either lever puts the spring connecting with it under tension and tends to draw downward the corresponding arm, rotating the vulcanite blade with it. To prevent movement of the blade until the spring has been put under a certain degree of tension, two slits, *g* and *g′*, are cut into the lower edge of the triangle, *f*. A releasing device, *i*, is pressed upward against the lower

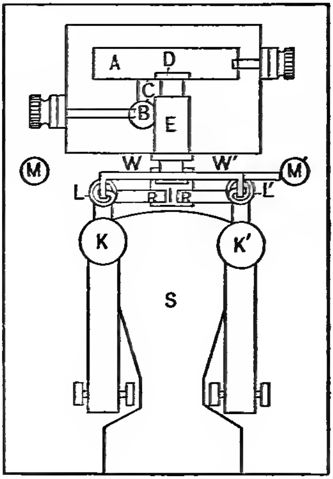

FIG. 13. Diagram of the operating device for the knife-blade key; horizontal view. Significance of letters the same as in Figs. 11 and 12. *s*, cavity in base for holding short-circuiting device.

edge of *f* by a stout spring, in such fashion that when either slit is engaged *f* is prevented from moving. Each of the levers, *k* and *k*,′ bears at its tip an arm, *r*, *r*′ (Fig. 13), which presses upon the releasing device, and when the lever is depressed to a certain point disengages it, allowing the blade to rotate. The amount of motion of the blade is limited by setting two posts, *m* and *m*′, at such positions that the lower apices of *f* strike them when sufficient movement has occurred.

After experimenting with various operating devices the one described above has been adopted as combining the greatest number of desirable features with the fewest defects. The two levers, *k* and *k*′, which are depressed alternately for making and breaking the circuit, are so placed as to lie naturally under the first and second fingers of either the right or the left hand. The springs, *l* and *l*′, need not be stiff, hence little pressure need be exerted upon the levers, and there is correspondingly little fatigue from continuous operation of the key. The springs are brought under tension only during the use of the instrument; when it is not in use, they hang free. Thus their stiffness does not vary with the lapse of time, as would be the case were one or the other under constant tension.

The Short-circuiting Device. A desideratum in any key which is to be used for stimulating tissues with single induction shocks is a device for short-circuiting automatically either the make shocks or the break shocks at the will of the operator. The instrument under consideration lends itself so readily to the incorporation of such a device that I shall include a brief description of one, believing that the value of the key is enough enhanced thereby to justify its inclusion. The entire mechanism, shown in ground plan in Fig. 13, is mounted upon a slab of vulcanite, which in turn rests upon a base of soapstone, slate, or other suitable material. The vulcanite is cut away between and underneath the levers, *k* and *k′*, as indicated at *s* (Fig. 13). A brass rod, *t* (Fig. 14), is mounted upon an axis, *u*, in such fashion that it can be rotated horizontally about this axis within the confines of the space, *s*. At the end of the rod is a mercury cup, *o*. Two binding posts, *p* and *p′*, stand

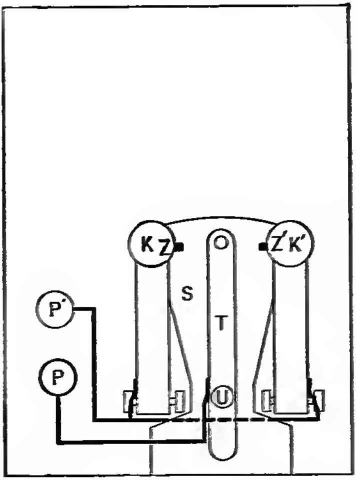

FIG. 14. Diagram of the short-circuiting device. *t*, brass bar, rotating horizontally about axis, *u*, and bearing mercury cup, *o*, which is in electrical communication with post, *p*. *z*, *z′*, platinum pins mounted upon levers, *k*, *k′*, and in electrical communication with post, *p′*.

at one margin of the base. From *p* a wire leads through the body of the vulcanite block to the rod, *t*, to which it is soldered near the axis of rotation of the rod. From *p′* two wires are carried through the block, one to the axis of rotation of the lever, *k*, to which it is soldered, the other to the axis of *k′*, where it is soldered likewise. Thus both levers are in electrical connection with the post, *p′*, and the rod, *t*, in similar connection with the post, *p*. Soldered to the levers, *k* and *k′*, at the points, *s* and *s′*, are pins of platinum projecting downward. These pins are so placed that the mercury cup, *o*, can be brought directly below one or the other of them according as *t* is rotated. Their length is so adjusted that the pin dips into the mercury when the lever is depressed enough to release the mechanism, but is clear of the mercury at all other times.

If the binding posts, *p* and *p′*, are connected in parallel into the secondary circuit of the inductorium and the rod, *t*, is rotated so as to bring the mercury cup below the lever which is pressed when the primary circuit is made (the left-hand one in this instrument) the make shocks are all short-circuited. Bringing the mercury cup below the other lever short-circuits all the break shocks. When the rod is placed in an intermediate position, neither makes nor breaks are affected. To prevent all possibility of accidental diversion of the secondary current into the hand of the operator, vulcanite shields are placed on the levers at the points where the fingers press upon them, and upon the handle by which the rod, *t*, is rotated.

In addition to its applicability for both make and break shocks this key has the advantage of preserving uniformity of action for a long time with little attention. In this respect it is superior even to platinum contact keys, which, as is well known, suffer from oxidation after prolonged use. There is no doubt, however, that well made automatic platinum-contact keys, properly looked after, give break shocks of sufficient uniformity for the general purposes of the physiologist.

CHAPTER X

THE INFLUENCE OF SECONDARY RESISTANCE AND OF CATHODE SURFACE

In the preceding chapters the scheme for measuring break shocks has been developed to the point where it becomes necessary to turn from the induction apparatus to the tissue to be stimulated and to inquire how variations in the tissue may modify stimulation strengths. Two possible modifying factors have been indicated (p. 14), as due to variations in the tissue; they are secondary resistance, and the manner of applying the electrodes.

The Relation of Tissue Resistance to Secondary Resistance as a Whole. The secondary circuit usually has a comparatively high resistance. Most inductoria used in physiological laboratories have secondary coils with resistances mounting into hundreds of ohms, and the resistances of the tissues undergoing stimulation are usually high likewise. In numerous determinations of the resistance of stimulated tissues I have met with only one or two under 1000 ohms and have found many exceeding 50,000 ohms.

Since the stimuli imparted by faradic currents as well as by those of galvanic origin arise from the cathode,* and since the resistance of the physiological cathodes must be small in comparison with that of the whole mass of tissue traversed by the current, we are justified in considering tissue resistance as external to the actual seat of stimulation, and need make no distinction between this and the other resistances that may be included in the secondary circuit.

The Method of Experimentation. In studying the influence of secondary resistance experimentally the usual procedure has been to introduce known, non-inductive, resistances into the secondary circuit and to observe the effect of their introduction upon the stimulating value of the shocks sent through the circuit. As a check upon this method some experiments were performed in which different amounts of tissue were included between the stimulating electrodes, and thus the resistance of the tissue itself was varied. This latter method is of course less certain than the former, since the inclusion of more or less tissue in the circuit may mean a variation in the number and irritability of the physiological cathodes involved.

Tissue resistances were determined by means of an ordinary Wheatstone bridge according to the Kohlrausch method, with an alternating current to avoid polarization, and a telephone in place of the galvanometer. Figure 15 is a diagram of the apparatus required. The average of three readings was always taken. This procedure, in the hands of one experienced in its use, gives results accurate within 4 or 5 per cent, a degree of accuracy sufficient for the purposes of this inquiry.

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* Chauveau: Journal de la physiologie, 1859, ii, pp. 490, 553. See also Biedermann: Elektrophysiologie, Jena, 1895, ii, p. 622.

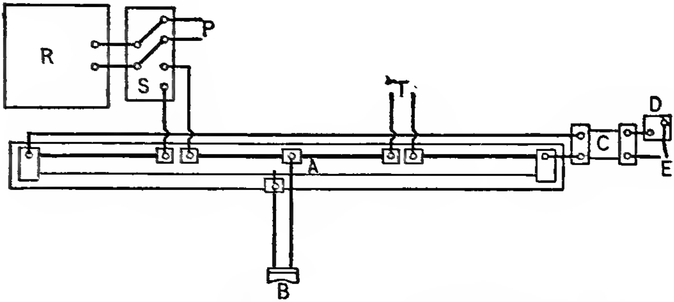

FIG. 15. Diagram of apparatus for measuring tissue resistance. *A*, Wheatstone bridge; *B*, telephone; *C*, small induction coil; *D*, battery for same; *E*, key for same; *T*, wires leading to tissue; *R*, resistance box connected with switch, *S*, in such fashion as to be available for use as known resistance of Wheatstone bridge, or as part of primary circuit, *P*.

Break shocks were used for determining the threshold of contraction. The expression for the value of the stimulus is Z, determined from the formula, $Z = \frac{M}{L} I$.

The Effect upon the Stimulus of Varying the Secondary Resistance. The effect upon the value of Z of varying the secondary resistance is shown in two representative experiments cited in Table VI. As appears

TABLE VI

The Influence of Secondary Resistance upon the Stimulating Values of Induced Currents

Experiment of Dec. 15, 1909. Resistance of Secondary Coil = 1400 ohms; of Tissue = 1700 ohms. Tissue = Frog's Gastrocnemius, Uncurarized.

Resistance in secondary circuit	3100	6100	10,100	15,100	18,100
Value of Z	4.96	6.81	9.45	12.45	14.1

Experiment of March 1, 1910. Resistance of Secondary Coil = 1400 ohms; of Tissue = 16,600. Tissue = Frog's Sartorius, Uncurarized.

Resistance in secondary circuit	18,000	28,000	48,000	68,000
Value of Z	3.97	5.24	6.8	9

from this table, stronger stimuli are required to produce a given physiological effect when the secondary resistance is high than when it is low. That there is a definite mathematical relationship between the effectiveness of the stimulus and the secondary resistance is shown by plotting these values as a curve. Such a curve for the first experiment of Table VI is given in Fig. 16. It is virtually a straight line having the general equation

$$Z = \frac{\beta (R + A)}{A}, \tag{1}$$

in which Z is the intensity of the shock required at resistance R to produce the desired effect, and β and A

are constants. This formula has been found to hold in all of the several hundred experiments, in which it has been applied. The value of the constant β in any

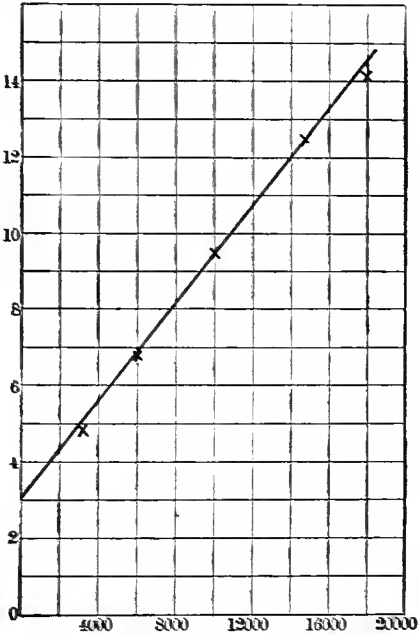

FIG. 16. Showing that the curve of increasing stimulus against increasing resistance is a straight line. Abscissæ represent values of Z; ordinates represent resistances in ohms.

given experiment can be determined geometrically by producing the curve to where it cuts the ordinate for zero resistance. According to Fig. 16, the value of β

for the experiment of Table VI from which that curve is derived is 3. Since this represents the value of Z, whose effect at zero resistance would equal that of the various other values of Z at their respective resistances, it affords a measure of the irritability of the physiological cathode where the stimulus actually arose, on the assumption that the resistance of the cathode is negligibly small. We have, therefore, in β an expression for the value of any stimulus as it affects the seat of actual stimulation, namely, the physiological cathode, irrespective of the resistance of the secondary circuit.

By a slight transposition of equation (1) the equation for β becomes:

$$\beta = \frac{ZA}{R+A}, \tag{2}$$

and if the value of Z for any secondary resistance is known, the actual or "specific" stimulus can be calculated from equation (2), provided only the value of the other constant, A, is known. For measuring stimuli with reference to the resistance through which they are applied there must be added to the determinations previously required, therefore, not only the secondary resistance, but a constant A.

Current Density an Important Factor. That the stimulating effectiveness of electric currents varies with their density has long been recognized,* although practical application of the fact has hitherto been reserved for galvanic stimulation. The expression for β shows that current density is a factor to be taken into account in measuring faradic stimuli as well.

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* Biedermann: Loc. cit., 1, p. 185.

The factor A in the expression $\beta = \frac{ZA}{R+A}$ is the provision by which allowance is made for the influence of current density. The stimulating effectiveness of dense currents is greater than of diffuse ones. In order that the expression for β agree with this fact the value of A must increase as the density of the stimulating current increases. Experimental evidence showing that A is actually larger for dense currents than for diffuse currents is contained in an experiment cited on p. 109, Chap. XII.

I do not know of any reliable method of determining the value of the constant, A, other than that used in this work, namely to establish experimentally two or more values of Z for different secondary resistances, and from these values compute the value of A. This can be done by means of the equation

$$A = \frac{Z_R R' - Z_{R'} R}{Z_{R'} - Z_R}, \tag{3}$$

in which Z_R and $Z_{R'}$ are the stimuli required, with resistances R and R' respectively, to produce the minimal contractions used as the index.

The Dependence of Factor *A* upon Inductorium Construction. In discussing the method of comparing one inductorium with another by the introduction of the factor L in the expression $Z = \frac{MI}{L}$, it was stated (p. 52) that this comparison is subject to a certain restriction as to secondary resistance. This restriction rests upon an observation of Gildemeister,* according to which, if two *dissimilar* inductoria are compared quantitatively by the method outlined here, in which the expression for the value of a stimulus is $Z = \frac{M}{L} \times I$, it will be found that although equal stimuli may yield corresponding values of Z from the two inductoria, with certain secondary resistances, when other secondary resistances are used equal stimuli will not give corresponding values of Z.

In earlier paragraphs of this chapter it was pointed out that the true or *specific* value of a stimulus is not afforded by the expression Z, but by the expression β, which depends not only upon Z but upon the secondary resistance and a constant A as well. The determination of A, as previously shown, is according to the formula

$$A = \frac{Z_R R' - Z_{R'} R}{Z_{R'} - Z_R},$$

in which Z_R and $Z_{R'}$ are stimuli which, with resistances

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* Gildemeister: Archiv für die ges. Physiologie, 1910, Bd. 131, S. 604.

R and R' respectively, have equal physiological effect. Since dissimilar inductoria fail to give corresponding values of Z at all secondary resistances, the value of A determined by this formula from one inductorium will not necessarily agree with its value as obtained from another. The value of A, therefore, does not depend solely upon the surface of the physiological cathodes, but in part also upon the construction of the inductorium.

This variation in the values of A determined from dissimilar inductoria, which might lead one to question the validity of the equation in which A is employed, i.e., $\beta = \frac{ZA}{R + A}$, serves in fact to confirm strongly the validity of that equation and the use of the expression β to signify the specific value of the stimulus. This confirmation rests upon the repeated observation that when equal stimuli are generated by dissimilar inductoria the *values of β are equal* even though the observed values of Z and the computed values of A may be quite divergent. An experiment illustrating this point is summarized in Table VII. Details of the construction of the inductoria used are given in Table VIII. The experiment shows that dissimilar inductoria give for equal break stimuli perfectly concordant values if all the factors which make up the final expression for stimulation strength are taken into account.

TABLE VII

Demonstrating that Equal Stimuli give Equal Values of β in the Equation $\beta = \frac{ZA}{R+A}$, when the Stimuli are generated by Dissimilar Inductoria

Inductorium.	H.	N.	B.
First sec. resistance	8,850 ohms	9,000 ohms	9,800 ohms
First Z	0.76	0.604	0.588
Second sec. resistance	25,500 ohms	25,600 ohms	26,400 ohms
Second Z	1.60	1.18	1.06
Calculated A	6,200	8,400	10,800
Calculated β	0.31	0.292	0.308

The differences in secondary resistance in corresponding columns are due to the different resistances of the secondary coils, it being necessary to include these resistances as part of the secondary circuit.

TABLE VIII

Details of Construction of the Inductoria used in this Study

Coil.	Length of secondary.	Turns in secondary.	Resistance of secondary.	Remarks.
	cm.			
A	12.5	10,000	850	Kronecker graduation
B	13.0	10,350	1400	Kronecker graduation
G	13.0	10,260	770	Kronecker graduation
E	6.5	5,000	300	Porter inductorium
H	9.3	6,000	450	
N	9.3	8,000	600	

Conditions in which the Specific Stimulus need not be determined. While we have in the formula $\beta = \frac{ZA}{R+A}$

a means of expressing the specific value of any break induction shock, no matter how the factors concerned in its production may vary, we must recognize that in the ordinary practice of the physiologist the attempt to make use of this formula presents very considerable difficulties. These difficulties, moreover, are chiefly in connection with the inclusion of the factors *R* and *A*, and we may well inquire how great errors are likely to arise in comparing faradic stimuli if these two factors are completely disregarded.

We must realize at the outset of this part of our inquiry that if comparisons are attempted between stimuli used under conditions of widely varying secondary resistance and divergent cathode surface, disregard of these two factors is sure to lead to erroneous conclusions; but probably in a majority of physiological experiments the stimuli to be compared are produced under conditions which tend to be closely similar. With regard to such cases as these we may properly inquire whether the factors under consideration need be taken into account.

Successive Stimulation of the Same Tissue. Probably the experiments in which accurate comparisons of stimuli are most needed are those in which a given tissue is to be stimulated successively. But in experiments of this class neither the tissue resistance nor the electrode surfaces undergo noteworthy variation during the course of the experiment and so do not enter as modifying factors.

Stimulation of Corresponding Tissues in Different Animals. Next in importance are cases in which it is desired to impart comparable stimuli to corresponding tissues through a series of experiments. Cases of this sort arise frequently in the course of physiological research, and I have therefore given them special consideration.

While this subject was before me there was being carried on in the laboratory at Harvard an investigation which involved, among other things, determining in a series of cats the threshold stimulus for producing extension of the wrist, when the stimulus was applied to the deep branch of the radial nerve below the elbow; and reflex flexion of the hind leg through stimulation of the tibial. Here was presented a typical example of the class of experiments described in the paragraph heading, and I therefore utilized it in the study of my problem. In several cases the threshold stimulus was determined when the tissue only was in the secondary circuit, and immediately afterward, the threshold when an additional resistance of 10,000 ohms had been introduced. I was thus able in these cases to compute the value of the constant A, and from it to obtain the solution of the equation for "specific" irritability, $\beta = \frac{ZA}{R + A}$. In the experiments of this series, ten in all, the secondary resistances ranged from 2800 ohms to 6000 ohms, averaging 3900 ohms. The values of *A* ranged from 4300 to 14,000, averaging 7800. The statistics for this series are given in Table IX.

TABLE IX

Illustrating the Tendency of β and Z to vary similarly in Direction and Extent. Z represents the Stimulus producing Just Perceptible Wrist Extension in Cat. Stimulus applied to Deep Branch of Radial Nerve

Date, 1910.	Secondary resistance.	Value of *A*.	Value of *Z*.	Value of β.	Ratio $\frac{\beta}{Z}$.
Aug. 8..................	6000	7500	2.77	1.54	.56
July 28..................	4400	5000	3.10	1.7	.53
Aug. 5..................	4800	8000	3.84	2.4	.62
Aug. 3..................	3400	7800	4.32	3.0	.70
Aug. 9..................	3000	9800	5.52	4.22	.77
Aug. 2..................	4600	9600	6.05	4.08	.68
Aug. 17..................	2800	4600	25.4	15.8	.62

As Above except that Stimulus was applied to Tibial Nerve, and Reflex Flexion of Hind Leg was Movement Evoked

July 18..................	3000	4,300	4.08	2.4	.59
July 22..................	4000	14,000	6.6	5.1	.77
July 20..................	3000	7,000	24.7	17.3	.70
Average..........	....	....	......	......	.65

Inspection of the table reveals a definite tendency of β to vary as does Z. The closeness of this tendency is brought out more strikingly, however, in Fig. 17, in which the ratios of β to Z in successive experiments are plotted. The horizontal line represents the average ratio of β to Z as determined in these experiments; the variations from this line of the different actual ratios are, as is seen, relatively inconsiderable, the greatest being 18.5 per cent, the average of all slightly under 11 per cent.

Assuming the data cited in Table IX to be fairly representative of the relations between β and Z that are likely to occur in experiments of the sort under consideration, to what extent are we justified in such experiments in making use of the values of Z for expressing quantitative relationships?

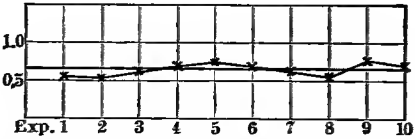

FIG. 17. Illustrating the relatively slight departures of individual ratios of β to Z from the average. Ordinates represent successive experiments; abscissæ represent ratios of β to Z. The horizontal line is drawn at the level of the average ratio.

The figures show clearly, I think, that all except the finest relationships are revealed with sufficient exactness by the values of Z. While one cannot always know certainly, in cases in which several nearly equal values of Z are under comparison, which will give smaller and which larger values of β, yet, if the experiments are carefully performed, one can be practically certain, whenever the values of Z differ by more than 15 or 18 per cent, that the larger Z means also a larger β. With this degree of accuracy assured, probably the demands of most researches of this class are fully met, and all such may safely disregard both the secondary resistance and the cathode surfaces.

Differing from the series of experiments quoted above in that they offer wider variations in both secondary resistance and electrode surface, and therefore greater likelihood of error if these factors be disregarded, is a series of observations on frogs' gastrocnemius muscles, carried out by myself.

In the series of eighteen experiments cited in Table X the secondary resistances ranged from 3100 to 13,000 and the values of A from 2600 to 13,500. Yet, in spite of these wide ranges in the values of the factors determining the relation of Z to β, this latter relation varies to a surprisingly moderate degree. The average ratio of β to Z is .49. The widest departures from this are ratios of .32 and .64, amounting to 35 per cent and 31 per cent respectively, while the average variation is only 15 per cent. If the experiments of Table X represent fairly the variations in secondary resistance and cathode surface likely to be met with in experiments on frogs' gastrocnemii, we can safely conclude that the values of

Z, obtained in any such experiment, represent the true relative values of the stimuli used within one-third.

TABLE X

Illustrating Tendency of *Z* and *β* to vary together. Frogs' Gastrocnemii stimulated directly

Date.	Secondary resistance.	Value of *A*.	Value of *Z*.	Value of *β*.	Ratio $\frac{\beta}{Z}$.
Feb. 24, 1910	5,400	6,900	6.12	3.4	.56
Oct. 28, 1909	6,500	6,000	6.24	3.0	.48
Dec. 15, 1909	3,100	5,000	11.9	7.35	.62
Jan. 19, 1910	8,400	4,800	12.2	4.45	.36
Feb. 17, 1910	6,800	7,500	12.35	6.5	.52
Feb. 24, 1910	6,400	4,200	12.5	4.95	.40
Feb. 18, 1910	5,000	4,800	12.7	6.2	.49
Jan. 31, 1910	11,400	13,500	12.95	7.0	.54
Mar. 7, 1910	5,400	4,800	14.6	6.86	.47
Feb. 18, 1910	5,500	5,500	14.6	7.3	.50
Nov. 18, 1909	7,700	4,200	15.35	5.40	.35
Feb. 10, 1910	13,000	6,000	16.8	5.30	.32
Jan. 31, 1910	10,400	9,000	19.2	8.90	.46
Dec. 13, 1909	5,000	5,000	19.9	9.96	.50
Jan. 31, 1910	6,200	10,500	22.1	13.9	.63
Feb. 18, 1910	5,000	4,800	22.8	11.2	.49
Feb. 17, 1910	6,000	10,500	24.7	15.7	.64
Nov. 4, 1909	3,200	2,600	41.5	18.6	.45
Average	....	....	......	......	.49

In a series of ten experiments on frogs' gastrocnemii stimulated through the sciatic, with resistances ranging from 6300 to 38,000 ohms, and values of *A* from 6000 to 23,000, the ratio of *β* to *Z* averaged .48, and the widest variation was a ratio of .28, amounting to 42 per cent, the average variation being 20 per cent. In the experiments cited in the two series above no attempt was made to keep conditions of tissue resistance and cathode surface approximately uniform. On the contrary, these conditions were purposely made to vary widely from one experiment to another. I feel, therefore, that they cover the range of variation likely to occur in ordinary experimentation.

These data seem to me to show that in the hands of a careful experimenter, who will take pains to keep his conditions of stimulation as uniform as possible, quantitative results of great value may be obtained without the labor involved in taking account of secondary resistance and cathode surface. By the use of the method outlined in previous chapters the strengths of stimuli employed in any given case may be expressed in terms of stimulation units, and if the conditions of experimentation, such as the nature of electrodes used, distance between them, and method of applying them, are carefully described, other experimenters can duplicate the stimuli very closely. Certainly this method allows comparisons of much greater accuracy than can be made by the existing methods of describing stimuli. It is highly important, however, that investigators attempting to use induction shocks quantitatively recognize fully the limitations upon accuracy which are involved in disregarding the factors under discussion. So long as there is no effort to draw conclusions which are not warranted by the degree of accuracy actually obtained, no harm will be done, but wherever the occasion exists for a high degree of accuracy in determining stimuli, secondary resistance and cathode surface must be taken into account.

A Standard of Inductorium Construction Necessary. In connection with this discussion of the circumstances in which the factors of secondary resistance and cathode surface may be disregarded, we must not forget that the structure of the inductorium is interwoven with the factor of cathode surface (see p. 78), in such fashion that the latter cannot be left out of account without error unless the former has been provided for. This provision is best made by adopting a standard of inductorium construction and using for quantitative purposes only instruments conforming reasonably to it. Thus we become at once independent of inductorium structure as a complicating factor, and are free to measure stimuli in many cases in the simpler manner discussed above.

The desirability of having a standard of inductorium construction for physiological and clinical use was recognized fully thirty years ago. In an attempt to establish one the Paris Electrical Congress of 1881 resolved at its session of September 28th that the form of inductorium at that time in use in the University of Berlin should be adopted as the standard.*

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* See Lewandowski: Elektrodiagnostik und Elektrotherapie, Wien und Leipzig, 1887, S. 212. Also Hoorweg: Die medicinische Elektrotechnik und ihre physikalischen Grundlagen, Leipzig, 1893, S. 128.

The dimensions of that inductorium are as follows:

	Primary	Secondary
Length of coil	88 mm.	65 mm.
Diameter of coil	36 mm.	68 mm.
Diameter of wire	1 mm.	0.25 mm.
Number of turns of wire	300	5000
Number of layers of wire	4	28
Resistance	1.5 ohms	300 ohms

Unfortunately for the general acceptance of these dimensions as standard, Kronecker * had, ten years earlier, proposed his well-known system of units, based on determinations made with inductoria having coils twice as long as the Berlin coils and each with twice as many turns of wire; and with the adoption of his graduation the large coils came into common use. By general consent among physiologists, therefore, rather than by any official action, inductoria having coils about 13 cm. long and having about 10,000 turns in the secondary are recognized as suitable for the uses of the investigator. In most well-equipped laboratories such inductoria are found, and there seems no valid reason why the general dimensions originally selected by Kronecker for his graduation should not be taken as standard. In a later paragraph (p. 92), observations will be cited which show that for quantitative work coils of this size are to be pre-

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* Kronecker: Arbeiten aus der physiologischen Anstalt zu Leipzig, 1871, S. 186.

ferred to the smaller ones recommended by the Paris Congress.

Assuming as the standard, then, an inductorium having coils about 13 cm. long and having in the secondary approximately 10,000 turns of wire, we may inquire how widely an inductorium can vary from this standard without introducing a significant error. For answering this question I have made observations with six inductoria, three of which are of "standard" construction and provided with Kronecker graduations, the other three selected to give increasing degrees of divergence from the standard. Details of the construction of the six inductoria are set down in Table VIII.

The results of my numerous experiments with these inductoria may be summarized as follows: The three standard coils, *A*, *B*, and *G*, give corresponding values of Z for equal stimuli and equal secondary resistances whatever the secondary resistance may be. In comparing them, therefore, the factor of inductorium construction does not enter.

In thirteen experiments in which coil *N* was compared with coil *B* the secondary resistances ranged between 2850 ohms and 25,000 ohms; the average percentage variation of Z_N* from Z_B was 6 per cent; the greatest variation was 11.6 per cent. Z_N was greater than Z_B

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* For convenience of expression a subscript is placed after the value of Z to indicate with which coil the value was obtained.

four times and Z_B greater than Z_N nine times. The small average percentage difference between the two coils, a difference only slightly greater than the probable experimental error, coupled with the fact that not all the variations are in the same direction, seems to me to show that in coils differing no more than these the influence of inductorium construction as a special factor can be disregarded without serious error.

An important effect of inductorium construction becomes manifest when coils *B* and *H* are compared. The average difference between Z_B and Z_H in twelve experiments was 16 per cent; in four of the twelve cases, moreover, the difference exceeded 24 per cent. Analyzing the series of experiments with reference to the secondary resistances it appeared that the high average difference is due to large differences in the experiments with high secondary resistance. Thus five experiments with secondary resistance above 10,000 ohms show an average difference between Z_B and Z_H of 25.7 per cent, while seven experiments with secondary resistances below 10,000 ohms show an average difference of only 4.5 per cent. In all five experiments with high secondary resistance Z_H was greater than Z_B. In the seven experiments with low resistance Z_H was larger than Z_B three times, smaller than Z_B twice, and equal to it twice.

This series of experiments shows that in inductoria differing even so widely as do coils *B* and *H*, inductorium construction is unimportant so long as secondary resistance is kept low. It is, however, of great importance whenever the secondary resistance is high.

The final series of comparisons was between coil *B* and the Porter inductorium, coil *E*. This yielded results of the same sort as the preceding comparison, but more marked. Only with very low secondary resistances were Z_B and Z_E equal, and Z_E became relatively more and more in excess of Z_B as the secondary resistance was increased. Table XI illustrates this relationship very clearly.

This last experiment brings out clearly the objection to the standard set by the Paris Congress of 1881 (p. 89). The Porter inductoria conform closely to that standard in all respects save that of diameter of the coils. As Table XI shows, the influence of secondary resistance upon stimulating value is very much more marked in

TABLE XI

Illustrating the Increasing Divergence of Z_E from Z_B with Increasing Secondary Resistance

Resistance in secondary circuit.	Z_B.	Z_E.	Percentage variation of Z_B from Z_E.
900 ohms	15.75	16.05	1.9
1,600 ohms	17.9	19.8	10.6
2,700 ohms	18.7	26.8	43.0
8,600 ohms	24.1	46.0	91.0
20,600 ohms	49.0	135.0	175.0

the small inductorium than in the larger one, so that while there are many sorts of experiments in which the investigator using a large coil is justified in disregarding secondary resistance, to do so would nearly always be unsafe if a small coil were being employed.*

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* The Porter inductorium with which this experiment was performed is of the old, or student, type. The new form, which is constructed in accordance with the Kronecker specifications, is well adapted for quantitative work.

CHAPTER XI

THE MEASUREMENT OF MAKE SHOCKS

In order that the scheme for making induction shocks quantitatively useful may be complete, a method for measuring make shocks must be added to the one already developed for break shocks. The method to be presented in this chapter is based wholly on experimental comparisons between make shocks and break shocks by the v. Fleischl method previously described (p. 56). That it is valid can scarcely be doubted in view of the large number of concordant experiments which support it.*

The expression for make shocks should, of course, be directly comparable with the one previously developed for break shocks. The factors of secondary resistance and cathode surface affect makes and breaks alike. We may take as a starting point from which to develop a formula for make shocks, therefore, the expression for break shocks which takes account of neither of these factors, namely $Z = \frac{MI}{L}$. The problem to be solved is how this expression must be modified so that the value

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* Martin: Am. Jour. of Physiology, 1909, xxiv, p. 276 *et seq.*

Z as applied to make shocks shall represent stimuli equal in intensity to those given by break shocks in which the value of Z is determined as above. The experimental procedure by which the problem was solved was as follows: A series of equal make stimuli were obtained with the secondary coil at various distances from the primary. The "calibration number" for each secondary position was then multiplied by the intensity of primary current employed at that position, and the products for each experiment were set down in a table.* For the inner positions of the secondary coil, positions which have relatively large values of $\frac{M}{L}$, the product $\frac{M}{L} \times I$ was nearly constant; as the secondary coil was moved out into the parts of the field where the values of $\frac{M}{L}$ are small, the product $\frac{M}{L} \times I$ became progressively larger the farther out the secondary coil was pushed, and consequently the smaller were the values of $\frac{M}{L}$. Numerous repetitions of the experiment gave precisely similar results.

These experiments indicated quite clearly the existence of a comparatively simple relationship between make and break stimuli, and also suggested a method for expressing the relationship mathematically in the simplest possible fashion, namely through the introduction of a single factor into the break shock formula, which when introduced would cause it to give equal values for Z for equal make stimuli. Study of the data showed that the factor to be introduced must be relatively larger the smaller the value of $\frac{M}{L}$, and must tend to diminish $\frac{M}{L}$. A constant number has this effect if it is subtracted from $\frac{M}{L}$. The formula modified in accordance with this idea becomes

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* For experimental data see Martin: *Loc. cit.*, p. 272.

$$Z_m = \left(\frac{M}{L} - K\right)I.^* \qquad (1)$$

In practically every experiment of a large series some number could be selected to be substituted for K in formula (1) with a fairly constant value of Z resulting. For each experiment the value of K had to be determined empirically, and it varied widely in different experiments. In all the experiments the values of K were negligibly small in comparison with the values of $\frac{M}{L}$ for secondary positions of 12 cm. or less.

The discovery of the above formula is a decided step toward the ultimate solution of the problem of measuring make shocks, but it is not a complete solution, since it offers no means of determining in advance what the value of K will be under any given set of conditions. The next step was to study a large series of experiments with reference to the conditions upon which the values of K depend.

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* To distinguish between break stimuli and make stimuli the former are represented by Z_b, the latter by Z_m.

It became apparent at an early stage of the investigation that make shocks, unlike breaks, are modified in intensity by changes in the *voltage* of the primary current. This observation suggested the grouping of all the experiments according to the primary voltage used in performing them. After this had been done the values of K for the different experiments of any group still differed widely, but now wherever the value of K was large the value of Z was also large and *vice versa*. This suggested at once a possible dependence of the value of K upon that of Z. To test this possibility the experiments of each group were plotted, values of K against values of Z. The resulting curve in each case is a straight line, having the simple equation

$$K = aZ. \tag{2}$$

Fig. 18 gives the curve for coil B obtained by plotting the experiments at 2 volts. The value of a given by this curve is 18. Substituting in equation (1) the value of K given in equation (2), we have

$$Z_m = \frac{M}{L} I - aZI. \tag{3}$$

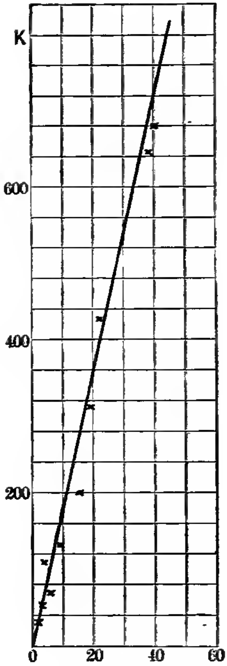

FIG. 18. Curve obtained when the values of Z given by the application of the formula $Z = \left(\frac{M}{L} - K\right) I$ to the experiments performed with a primary voltage of 2 are plotted against the values of K used in these experiments. Abscissæ represent values of K; ordinates represent values of Z. The equation for this curve is $K = 18\,Z$.

This solved for Z_m and simplified gives

$$Z_m = \frac{\frac{M}{L}}{\frac{1}{I} + a}, \qquad (4)$$

an equation which enables us to determine the value of make stimuli at any given primary voltage, for which the value of a is known.

There remains now for the completion of the make shock formula only the establishment of a definite relationship between the values of a at various primary voltages and the voltages themselves. To determine whether such a relationship exists another curve was plotted, primary voltages against values of a previously determined. This curve is represented in Fig. 19. It has the simple equation

$$E = a \cdot C, \tag{5}$$

in which C represents a constant. Substituting in equation (4) the value of a given by equation (5), we have

$$Z_m = \frac{\frac{M}{L}}{\frac{1}{I}+\frac{C}{E}}; \tag{6}$$

which is the general equation for make induction shocks. The value of C is fixed for each inductorium. For the one with which this equation was developed, coil B, its value is 36.

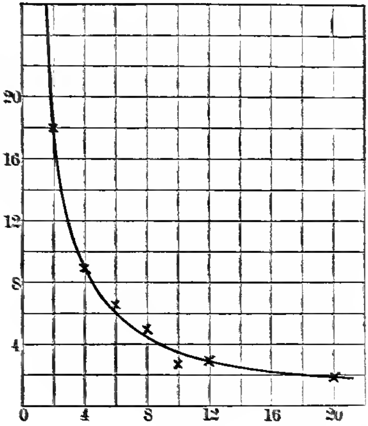

FIG. 19. Curve obtained by plotting against the different primary voltages used in these experiments the values of a obtained from curves plotted as in Fig. 1. The equation for this curve is $E \times a = 36$. Abscissæ represent values of a; ordinates represent primary voltages.

Comparison of the General Formulæ for Break and Make Stimuli. If the general equation for break shocks be written in the same form as the one for make shocks and the two placed side by side, the simple mathematical relationship existing between make and break stimuli becomes apparent. Written thus, the break shock formula is

$$Z_b = \frac{\frac{M}{L}}{\frac{1}{I}}.$$

Comparing this with the make shock formula,

$$Z_m = \frac{\frac{M}{L}}{\frac{1}{I} + \frac{C}{E}},$$

the difference between them is seen to be wholly in the denominator, and to consist of the addition of a simple expression to the denominator of the break shock formula to give the one for make shocks. Inasmuch as increasing the denominator of a fraction diminishes the value of the fraction, the formulæ express the well-known fact that make shocks are weaker than break shocks produced under equivalent conditions.

In the formulæ as here presented the numerators express the influence upon the value of Z of the position of the secondary coil with respect to the primary. The denominators express the influence upon Z of the intensity of the primary current, and for make stimuli the influence of its voltage also. Since the numerator is the same in both formulæ, i.e., $\frac{M}{L}$, it follows that however the break stimulus Z_b may compare with the make stimulus Z_m, changing the value of $\frac{M}{L}$ by moving the secondary coil does not affect the relationship between them. To illustrate, if we suppose the break stimulus to be twice as intense as the make stimulus when the secondary coil is at zero, the break will continue to be twice as intense as the make wherever the secondary coil is placed, provided, of course, that all other conditions remain constant.

Since the difference between the two formulæ is wholly in their denominators, we may expect careful analysis of these to yield a full understanding of the conditions upon which depend the relationships between make and break stimuli. The denominator of the make shock formula will always be larger than that of the break formula, but the amount of difference between the two will vary greatly according to the relative values of $\frac{1}{I}$ and $\frac{C}{E}$. This can best be shown by a concrete case. Let us first compare the values of Z_b and Z_m in a hypothetical experiment with coil *B* in which a primary current of 0.0005 ampere at 20 volts is employed. The expression for Z_b is

$$\frac{\frac{M}{L}}{2000}.$$

For Z_m the expression is

$$\frac{\frac{M}{L}}{2000 + \frac{36}{20}} = \frac{\frac{M}{L}}{2001.8}.$$

The difference between the stimulating intensities of the two sorts of shocks is in this case less than one-tenth of one per cent. Compare now the values of Z_b and Z_m when a primary current of 0.4 ampere at 2 volts is used. The expression for Z_b is

$$\frac{\frac{M}{L}}{2.5},$$

and for Z_m is

$$\frac{\frac{M}{L}}{2.5 + \frac{36}{2}} = \frac{\frac{M}{L}}{20.5}.$$

In this case the break shock is more than eight times as intense as the make.

The above illustrations present in concrete form the effects upon the relation between break and make stimuli of variations in intensity and voltage of the primary current. These effects may be stated in general thus: *The higher the voltage of the primary current and the less its intensity, the more nearly will make shocks equal break shocks: conversely, the lower the voltage of the primary current and the greater its intensity, the more will break shocks exceed make shocks.*

The make shock formula shows that make stimuli do not vary directly with the intensity of the primary current as break stimuli do. Although make shocks increase absolutely with every increase in primary intensity, other conditions remaining uniform, the increase is relatively slight when primary intensities of considerable magnitude are compared. For example, if with coil *B* a 2 volt primary current be increased from 0.5 ampere to 1.0 ampere, the make stimuli will be increased only 5 per cent, while break shocks under the same circumstances would be doubled.

This peculiarity of relation of make shocks to primary currents of high intensity shows itself very strikingly in many experiments in which minimal muscular contractions are used as indicators of stimulation strength. In the outer parts of the field of the inductorium, where the values of $\frac{M}{L}$ are small, primary currents of high intensity must be employed to give shocks sufficient to elicit visible response. I have often found when studying make shocks, especially with primary currents of low voltage, that as the secondary coil was pushed out to a point where primary currents of 0.1 or 0.2 ampere failed to elicit response, no increase of primary intensity up to the limits of my apparatus would raise the stimulus to the threshold. This frequent failure of relatively enormous primary currents to give detectable make stimuli was wholly inexplicable until the development of the make shock formula made its meaning clear.

Although the make shock formula

$$Z_m = \frac{\frac{M}{L}}{\frac{1}{I} + \frac{C}{E}}$$

presents the appearance of some complexity, as a matter of fact it is a comparatively easy task to derive the value of C, which is the only new constant the equation requires, and with the constant once established the use of the formula is perfectly simple. To determine how laborious is the task of determining the value of C, an inductorium was taken which had been previously calibrated for break shocks, and seven experiments were found to yield sufficient data to establish conclusively the value of the constant.

The experimental procedure is that described on p. 95. The interpretation of the results so as to establish the constant depends upon recognition of the fact that in such experiments as these the value of Z_m for the inner positions of the secondary coil, where threshold stimulation is obtained with very small primary currents, is practically independent of the value of the constant; whereas the value of Z_m for secondary positions far out on the scale, where heavy primary currents must be used, can be correctly determined only if the constant is accurately known.

By transposition of the equation

$$Z_m = \frac{\frac{M}{L}}{\frac{1}{I} + \frac{C}{E}},$$

we obtain the formula for the constant

$$\frac{C}{E} = \frac{\frac{M}{L}}{Z_m} - \frac{1}{I}. \qquad (7)$$

By taking advantage of the fact above noted, that the value of Z_m for the inner secondary positions is independent of C, we can obtain Z_m for any given experiment by taking the product of $\frac{M}{L} \times I$ for these positions. Since the value of Z_m is assumed to be constant throughout the experiment we can apply this value to the solution of equation (7), using the data obtained at the outer secondary positions to give $\frac{M}{L}$ and $\frac{1}{I}$. From four experiments at 2 and 4 volts were obtained by this method the following values of C: 8.16, 8.0, 6.8, 9.0, 8.0, 9.8, 8.0, 5.2, 8.0. The average of these is 7.9. The nearest round number, 8, was taken as a sufficiently close approximation to the constant, and was applied to three other experiments at primary voltage ranging from 2 to 12. When so applied, constant values of Z_m were obtained,* thus proving the correctness of the determination.

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* For data see Martin: Amer. Jour. of Physiology, 1909, xxiv, pp. 279 and 280.

CHAPTER XII

ERRORS TO BE AVOIDED

INCIDENTAL results of the several years of study spent in developing the quantitative method here presented have been to emphasize the importance of certain precautions, and also to reveal the errors committed by some users of induction shocks in their efforts to make quantitative comparisons by indirect methods.

Probably the most urgent general precaution calling for discussion is that of maintaining good electrical contacts throughout. In a mechanism so complicated as that shown in Fig. 8 loose contacts which may easily escape observation are likely to render quantitative observations completely valueless. The user of the apparatus must keep continually in mind the importance of maintaining tight contacts, and by frequent inspection must assure himself that they are so. The sliding contacts provided for the secondary coils in some forms of inductoria are very untrustworthy and should not be used if fixed ones are available.

In applying stimulating electrodes one must have in mind that the induced current stimulates at the *cathode*, and must know which electrode this is. A simple means of distinguishing the poles of the secondary circuit is to apply them to a sheet of filter paper moistened with a mixture of starch paste and potassium iodide solution. If a strong primary current is made and broken rapidly, and the secondary makes or breaks are short-circuited each time, a blue deposit presently appears at the anode, indicating the accumulation there of iodin ions which react with the starch. It should be remembered that make shocks and break shocks are opposite in direction, so that the pole which is revealed as the anode for break shocks is the cathode for makes.

The development of a mathematical expression for the influence of secondary resistance on stimulating value has shown the fallacy of a method sometimes employed for varying stimulating strengths quantitatively by including known resistances in the secondary circuit and assuming that the strength of stimulus is reduced in exact proportion with the increase of resistance. As the equation (p. 76) shows, the strength of stimulus not only does not vary in exact proportion with the resistance, but the relationship actually existing is not apt to be the same in two successive experiments, owing to the interrelation between secondary resistance and cathode surface.

This same interrelation explains the error of another procedure which has sometimes been employed for the purpose of overcoming inequalities in stimulation strength due to differences in secondary resistance, namely the introduction of a very high additional resistance into the secondary circuit, thereby making fluctuations in tissue resistance relatively negligible. That this device is perfectly adequate in experiments in which a single tissue of varying resistance is under examination is of course obvious; there being under such circumstances no variation in cathode surface. But in experiments in which different tissues are being compared the introduction of high additional resistance into the secondary circuit is more apt to be misleading than otherwise because of the cumulative effect of variations in cathode surface. The point can best be illustrated by a concrete example:

Experiment of March 7, 1910. — Frog's gastrocnemius muscle stimulated directly. In the first test the cathode was in contact with the surface of the muscle, but did not penetrate it. When the tissue only was in the secondary circuit, the total secondary resistance was 17,000 ohms. A minimal contraction was secured with a value of Z equal to 6.6. When 70,000 ohms' additional secondary resistance was introduced, the value of Z was 16.8. By calculation the value of A was found to be 28,000, and that of the specific stimulus β to be 4.1.[*] In the second test the cathode was thrust directly through the muscle tissue; the secondary resistance was 5400 ohms; the value of Z was 6.1. When 70,000 ohms' additional resistance was introduced, the value of Z was 40.5. The calculated value of A was 7000, and of β 3.45. In this case the values of Z as determined with the tissue only in the secondary circuit represent much more nearly the true relationships between the stimuli than do the values as determined with a large additional resistance in the circuit. In reality the stimulus applied in the first test

[*] For the equations used in this calculation see p. 77.

was stronger than in the second, whereas, if reliance were placed upon the results given when the high additional resistance was in circuit, it would appear that the second stimulus was more than twice as strong as the first. The subjoined tabulation will serve to emphasize the error:

	Z (tissue only)	Z (70,000 ohms added)	β
First	6.6	16.8	4.1
Second	6.1	40.5	3.45
Ratio of 1st to 2d	1.08	0.41	1.19

In determining specific stimulation values by means of the expression $\beta = \frac{ZA}{R + A}$, particularly when the tissues stimulated have high resistances, errors in determining the value of A may easily vitiate the results. It will usually be found desirable to determine values of Z for at least three secondary resistances in addition to the tissue resistance itself. If the values of Z thus obtained are plotted against their respective resistances the curve which they yield reveals at once whether errors have been made in the determinations. The curve should be a straight line, cutting the ordinate for zero resistance at some point above the base line. Minor errors may be allowed for by drawing the curve to make them balance one another. This precaution is unnecessary when tissues of low resistance are studied, since with them small errors in determining A are less significant.

These are among the less obvious sources of error in quantitative work, and are therefore discussed here. The more apparent ones need not be mentioned, since they are sure to suggest themselves to any user of the method here presented.

In the use of this quantitative method, as in most procedures involving numerous factors, a technique, which seems at the outset highly complicated, becomes with practice easy to carry out. Its inclusion as part of the experimental routine of the working physiologist is therefore justified. To facilitate such inclusion is the purpose of this manual.

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